CEMENTS,
MORTARS AND CONCRETES

THEIR PHYSICAL PROPERTIES

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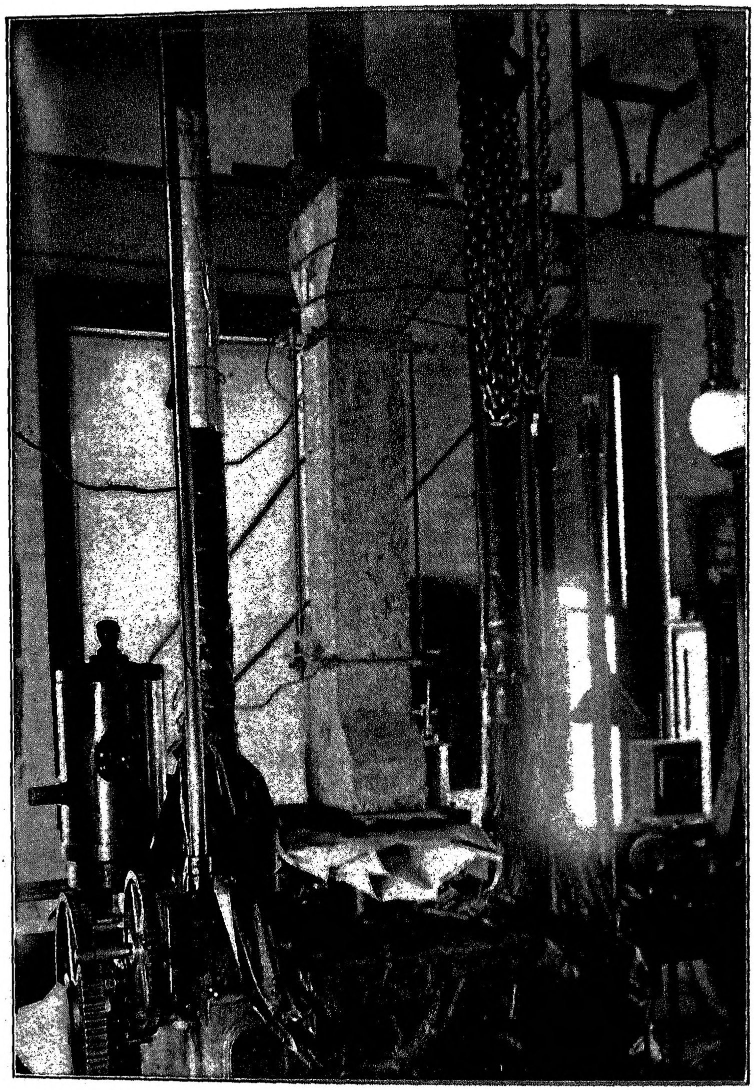

Showing Method of Determining Elastic Behavior of Concrete Bars, 6x6-Inches in Cross-Section. Specimen, with Electric Extensometer Attached, Mounted for Compression in the 150,000 Pound Emery Testing Machine of Columbia University.

INTRODUCTION.

The purpose of this treatise has been to set forth as concisely as possible the physical properties of cement and cement mixtures, with principal reference to those properties which concern the engineer. The results of investigations made upon these materials have been examined with great care. Engineers desiring such data on cements, mortars and concretes, have hitherto been obliged to refer to numerous scattered articles and books. It has been the author's object to abstract, classify and summarize all the reliable data extant, filling in certain gaps with data of his own. The following headings outline, for the greater part, the scope of the work:

General Physical Properties:

- Changes in Volume When Setting.
- Coefficient of Expansion Due to Temperature Changes.
- The Action of Sea Water and Salt.
- Porosity and Impermeability.
- Effect of Freezing.
- Adhesion of Iron Rods to Cement Mixtures.
- Fatigue of Cement Mixtures.

General Elastic Properties:

- Tensile and Compressive Properties.
  - *Coefficient of Elasticity.*
  - *Elastic Limit.*
  - *Ultimate Resistance.*
- Flexural Properties.
  - *Coefficient of Elasticity.*
  - *Modulus of Rupture.*
- Shearing Resistance.

The sources from which the experimental data have been obtained are furnished, in every instance, with those data; it is

therefore unnecessary to give separate credit to the various experimenters at this point. It is proper to say, however, that use has been made only of those results which gave evidence of careful work, so that no conclusions might be invalidated by reason of the unreliability of the experiments. Free use has been made of the Annual Reports of the Watertown, Mass., Arsenal, of the Transactions of the American Society of Civil Engineers, and of the Proceedings of the Institution of Civil Engineers of Great Britain. The experiments, not previously published, made under the author's direction in the laboratories of Columbia University, have also been included.

It is believed that the results obtained relating to the elastic properties of the material, such as the values of the coefficients of elasticity and the ultimate strengths, have been so analyzed that these values may be determined in advance, for any mixture, within small limits of error; but future experiments and future improvement in the manufacture of cement mixtures may cause considerable changes in these figures.

In order that a cement's physical peculiarities may be more clearly comprehended, it has been thought advisable to consider as a preliminary some of the chemical characteristics of cements. In connection with the discussion of chemical compositions, the theories of the setting of cements have therefore been analyzed, and it has been possible to abstract, in an appendix, Mr. Clifford Richardson's theory as to the constitution of Portland cements. In addition, a chapter, together with an appendix, treating briefly of the ordinary commercial tests has been included.

M. S. F.

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CHAPTER I.

CHEMICAL PROPERTIES OF CEMENT.

Definition—Cement is a material which has the property of setting and hardening under water, and is composed principally of lime, silica and alumina. Two forms of cement are commonly recognized, natural and Portland, and to these the following pages will be entirely restricted. The difference between these forms is principally one of manufacture; the basic principles in both varieties are the same.

Article 1.—Theories of Setting.

The proper chemical constitution of cements involves the consideration of the theory of the setting and hardening of cements, the reasoning concerning which is, at the present time, not unanimous. Chemists have not definitely determined the chemical changes that occur when water is added to dry cement; but the conclusions reached by Le Chatelier in 1887 and by the Newberrys in 1897 have been accorded more weight than those of others.

Le Chatelier's Theory (Annales des Mines, 1887, p. 345).

Le Chatelier considers that when the raw materials of a cement have been burned two different sets of compounds possessing the property of setting and hardening upon the addition of water may be formed.

In the first case he considers that the finished material contains lime (CaO) just sufficient in amount to combine with the silica (SiO_2) and alumina (Al_2O_3) to form tricalcic silicate ($3CaO.SiO_2$) and tricalcic aluminate ($3CaO.Al_2O_3$). These compounds, upon hydration, set and harden. He finds it unnecessary to provide lime

mixture, since the calcic ferrites that might form fall to powder upon the addition of water. Magnesia (MgO) and lime he considers as possessing equivalent properties, and, therefore, interchangeable. In this case, then, no multiple silicates of alumina and lime are formed; and in order that the finished cement may have no free lime existing in it, Le Chatelier states that the proportion of lime and magnesia to silica and alumina should be subject to the following conditions:

$$\frac{CaO+MgO}{SiO_2+Al_2O_3} \leqq 3$$

The objection to the presence of free lime or magnesia is due to the fact that they blow or expand in volume when acted upon by water; disintegration of the cement follows and it becomes unfit for use.

For the second condition Le Chatelier believes that only tricalcic aluminate and a silico-aluminate of lime, represented by $2SiO_2.Al_2O_3.3CaO$, are formed, and that the Fe_2O_3 acts similarly to Al_2O_3 in the case of multiple silicates and need not be separated from it.

For this case Le Chatelier states the condition of the proportions of the constituents as follows:

$$\frac{CaO+MgO}{SiO_2-Al_2O_3-Fe_2O_3} \geqq 3$$

The Newberrys' Theory (J. Soc. Chem. Ind., 1897, p. 889).

The conclusions reached by Spencer B. and W. B. Newberry are quite different; it is their belief that the compounds that harden, upon hydration, are tricalcic silicate and dicalcic aluminate, and not tricalcic aluminate.

Tricalcium silicate requires 2.8 parts of weight of lime to 1 part of silica, and dicalcic aluminate requires 1.1 parts of lime to 1 of alumina. The Newberry formula for a theoretically perfect cement is therefore:

$$\frac{2.8\ Silica+1.1\ Alumina}{Lime}=1$$

In this equation the materials represent percentages of weight in the cement.

The Newberrys also conclude that Fe_2O_3 acts similarly to Al_2O_3, but should not be allowed in excess of 5 per cent. In this they differ from Le Chatelier. Again, Le Chatelier's formula places magnesia and lime of equivalent value in a cement; the Newberrys, on the contrary, consider magnesia inactive, and to perform no useful function.

One general opinion concerning the magnesian compounds in cement is that they cause the first or preliminary setting of the cement, but that they expand and crack after aging. In all cases the calcic compounds are considered to be the ones which harden with age, and they are the compounds which cause ultimate strength. On account of this possibility of blowing, it is therefore the common practice at present to limit the presence of magnesia to 5 per cent. Cements containing up to this limit have not been shown to be inferior.

Another theory as to the first or quick setting properties of cement attributes these properties to the presence of calcium-aluminate, and the final or ultimate strength to the calcium-silicate only. It is difficult to reconcile these conflicting opinions.

Other chemical elements which appear in a cement are believed to be of no practical importance, and none other will be considered, except plaster of Paris or sulphate of lime, $CaSO_4$, which is added in percentage never exceeding 2 per cent., for the purpose of causing a slower setting of the cement. This is a common practice, and its effect on the strength of the cement will be considered later.

Art. 2.—Chemical Analyses.

It will be interesting to examine the different chemical compositions of cement as they have been recorded by different analysts. It will be found that the variations of the different constituents, on the whole, are very slight.

Portland Cements—Table I. exhibits the values of analyses as taken from the report of the Watertown Arsenal "Test of Metals, etc.," for 1901.

TABLE I.—PORTLAND CEMENTS.

Brand	Location of Works	Silica SiO_2	Oxide of Iron Fe_2O_3	Alumina Al_2O_3	Lime CaO	Magnesia MgO	Sulphur Trioxide SO_3	Carbon Dioxide CO_2
Alpha	Easton, Pa	20.60	2.91	11.20	59.00	3.25	1.40	1.34
Atlas	Northampton, Pa.	18.32	3.36	11.22	60.00	3.78	1.40	1.92
Lehigh	West Coplay, Pa.	23.84	1.30	8.12	61.58	2.48	1.60	1.08
Star (with plaster)	Siegfried, Pa	22.00	2.50	9.00	59.90	3.50	1.98	0.75
Star (without ")	" "	22.45	2.53	9.27	60.27	3.59	0.60	1.00
Storm King	Akron, N. Y	22.94	2.90	6.30	43.74	*20.72	2.83	1.00
Whitehall	Cementon, Pa	20.30	2.95	10.87	62.15	2.51	1.10	0.12
Alsen	Germany	20.42	2.10	11.00	57.50	2.53	2.26	4.19
Dyckerhoff	"	20.04	3.95	7.48	63.02	1.23	1.62	3.00
Josson	Belgium	22.92	2.46	7.98	63.39	Trace	1.28	1.97
Average		21.38	2.70	9.23	60.76	2.54	1.61	1.64

*Not included in average.

TABLE II.—PORTLAND CEMENTS.

Brand	Location of Works	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Alpha	——	22.62	8.76	2.66	61.46	2.92	1.53
Atlas	——	21.96	8.29	2.67	60.66	3.43	1.43
Giant	Jordan, N. Y.	19.92	9.83	2.63	60.32	3.12	1.13
Saylors	Coplay, Pa	22.68	6.71	2.35	62.3	3.14	1.88
Vulcanite	Vulcanite, N. J.	21.08	7.86	2.48	63.68	2.62	1.25
Empire	Warner, N.Y.	22.04	6.45	3.41	60.92	3.53	2.73
Jordan	——	21.86	7.17	3.73	61.14	2.34	1.94
Diamond	Middlebranch, Ohio	21.8	7.95	4.95	61.9	1.64	.79
Sandusky	——	23.08	6.16	2.9	62.38	1.21	1.66
Bronson	Bronson, Mich	20.95	9.74	3.12	63.17	.75	.86
Whitecliffs	Whitecliff, Ark.	22.93	—10.33—		64.67	.94	1.05
Average		21.90	7.89	3.09	62.04	2.33	1.49

TABLE III.—EUROPEAN PORTLAND CEMENTS.

Brand	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
White label, Alsen	20.48	7.28	3.88	64.3	1.76	2.46
Dyckerhoff	20.64	7.15	3.69	63.06	2.33	1.39
Germania	22.08	6.84	3.36	63.72	1.32	1.82
Hemmoor	21.14	5.95	4.01	63.24	1.44	1.47
Lagerdorfer	23.55	7.47	2.4	61.99	1.42	1.07
Brook, Shoobridge & Co	22.2	7.35	4.77	61.46	1.35	1.87
Francis	22.18	8.48	5.08	61.44	1.34	1.56
Condor	23.87	6.91	2.27	64.49	1.04	.88
Candlot, French	22.3	8.5	3.1	62.8	.45	.7
Boulogne, French	22.3	7.	2.5	64.62	1.04	.75
Average	22.07	7.29	3.51	63.12	1.35	1.40

Table II. shows similar quantities obtained from analyses of American cements, compiled by Ries & Eckels, in "Lime and Cement Industries of New York," 1901, page 705.

Table III. is taken from the same book and exhibits the composition of some European Portland cements.

TABLE IV.

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3
60.94	23.23	7.75	3.04	2.14	1.56

Table IV. shows the average results of chemical analyses made on thirty-eight samples of cement used in submarine work on the Charlestown bridge, Boston, by the Boston Transit Commission, as published in their report for 1900.

Finally, owing to the interest which has been aroused by the novel conditions of manufacture, Table V., containing an analysis of the Edison Portland Cement Company's cement, is given. The analysis is taken from a reported test by Lathbury & Spackman, Incorp., of Philadelphia, and was published in the "Engineering Record" December 26, 1903.

TABLE V.

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO
62.71	20.14	7.51	3.33	2.34

These tables show very uniform results; in general, the percentages of the constituents are as follows:

CaO	averages..........	62%
MgO	"	2%
SiO_2	"	22%
Al_2O_3	"	8%
Fe_2O_3	"	3%

Inserting these values in the Newberry formula, the result obtained is

$$\frac{2.8\times22+1.1\times8}{62}=1.14,$$

or an error of 14 per cent. as compared with a theoretically perfect cement.

By substitution the first of Le Chatelier's formulas reduces to

$$\frac{62+2}{22+8}=2.13;$$

and the second to

$$\frac{62+2}{22-8-3}=5.82$$

These values are respectively smaller and greater than 3, as they should be; but they give no indication of the standard of excellence obtained.

Natural Cements—The following tables show the average analyses of both European and American natural cements:

Table VI. is taken from the Watertown Arsenal report on "Test of Metals" for 1901; Table VII. from U. Cummings's

TABLE VI.—NATURAL CEMENTS.

Brand	Location of Works	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	CO_2
Akron Star	Akron, N.Y.	20.40	2.56	6.22	40.64	25.80	2.91	1.47
Austin	Mankato, Minn.	19.02	1.24	8.96	41.18	26.58	1.27	1.75
Bonneville Improved	Siegfried, Pa.	30.40	2.60	10.36	52.12	0.21	1.24	3.07
Hoffman*	Rosendale, N. Y.	25.00	2.27	8.93	39.30	16.18	1.40	2.66
Mankato	Mankato, Minn.	27.70	1.86	7.06	37.00	22.63	1.23	2.46
Newark & Rosendale	Whiteport, N.Y.	28.71	3.60	5.88	27.00	30.00	1.30	3.52
Norton	Binnewater, N.Y.	26.66	3.02	11.48	38.33	16.41	1.35	2.75
Obelisk	Akron, N. Y.	23.70	3.30	16.70	37.00	15.30	1.98	2.00
Potomac	———	32.00	2.70	8.79	33.89	18.10	1.31	3.20
Average		25.95	2.57	9.37	38.49	19.02	1.55	2.54

*Contains 4.26 per cent. of Oxides of Sodium and Potassium.

"American Cements," and Table VIII. from analyses, reported by D. J. Whittemore, in the Transactions of the American Society of Civil Engineers, 1880.

The American natural cements of Table VII. cover a wide range of territory.

TABLE VII.—NATURAL CEMENTS.*

Brand and Location of Works.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
Buffalo Hydraulic Cement; Buffalo, N. Y.	24.3	2.61	6.2	39.45	6.16
Utica, Ill	34.66	5.1	1.	30.24	18.
Milwaukee, Wis.	23.16	6.33	1.71	36.08	20.38
Fernleaf Brand; Louisville, Ky.	26.4	6.28	1.	45.22	9.
Hulme; Louisville, Ky.	25.28	7.85	1.43	44.65	9.5
N. L. & C. Co.; Rosendale, N. Y.	30.5	6.84	2.42	34.38	18.
Rocklock; Rosendale, N. Y.	29.98	6.88	2.5	33.23	17.8
N. Y. & R.; Rosendale, N. Y.	30.84	7.75	2.11	34.49	17.77
Hoffman; Rosendale, N. Y.	27.3	7.14	1.8	35.98	18.
Norton High Falls; Rosendale, N. Y.	27.98	7.28	1.7	37.59	15.
Cumberland, Md.	28.38	11.71	2.29	43.97	2.21
Napanee, Ont.	19.9	5.92	1.14	46.75	16.
Newman; Akron, N. Y	22.62	7.44	1.4	40.68	22.
Cummings; Akron, N. Y.	26.69	7.21	1.3	43.12	19.55
South Riverside, Cal.	24.34	8.56	2.08	61.62	.4
Brockett; Ft. Scott Hydraulic, Kansas City, Mo.	23.32	6.99	5.97	53.96	7.76
Utica Brand; Utica, Ill.	27.6	10.6	.8	33.04	7.26
Shepherdstown, W. Va.	33.42	10.04	6.	32.79	9.59
Howard Hyd. Cem.; Cement, Ga	22.58	7.23	3.35	48.18	15.
Hydraulic Cem. Rock; Platte River, Neb.	22.44	6.7	2.	32.73	.67
Mankato, Minn.	28.43	6.71	1.94	36.31	23.89
St. Louis Hydraulic Cement, near E. Carondelet, Ill.	22.21	16.48	1.67	39.64	17.5
Barnesville, Ohio	32.06	21.27	2.11	35.56	7.
Warnock, Ohio	28.45	2.24	2.	56.	10.
Austin, Minn.	18.59	9.14	1.	40.7	27.
Round Top Cement; Hancock, Md.	28.02	10.2	8.8	44.48	1.
Balcony Falls, Va.	25.15	8.	3.28	49.53	13.78
Average	26.40	8.17	2.55	41.12	12.97

*From "American Cements," by U. Cummings

TABLE VIII.—NATURAL CEMENTS.

Cement No.	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3
1	45.17	16.52	23.40	8.07	2.45
2	36.32	14.47	24.50	14.32	2.93
3	33.97	15.21	28.04	12.82	4.60
4	40.75	25.25	22.22	8.68	1.18
Average	39.05	15.36	24.54	10.97	2.79

The results show that

CaO averages .... 40 %
MgO " .... 15 %
SiO_2 " .... 26 %
Al_2O_3 " .... $8\frac{1}{2}$%
Fe_2O_3 " .... 1 %

It will be seen that the greatest difference between the natural and Portland cement is in the varying proportions of the lime and magnesia contents; the other constituents remain about the same. Using the average figures of the natural cements given on the preceding page, the Newberry formula becomes

$$\frac{2.8\times 26+1.1\times 8\frac{1}{2}}{40}=2.05;$$

the first of Le Chatelier's formulas becomes

$$\frac{40+15}{26+8\frac{1}{2}}=1.6$$

and the second,

$$\frac{40+15}{26-8\frac{1}{2}-2\frac{1}{2}}=3.67$$

None of these formulas furnishes results comparable with theoretic requirements, in the case of the Newberry formula probably on account of the neglect of the magnesia.

As a conclusion it is evident that a chemical analysis may give no final indication of the quality of the cement. Adulteration of the cement with inert material, such as slag, may be discovered. Certain materials, such as magnesia or plaster of Paris, may be found present in too large quantities; but it seems evident that a poor cement may be due more to imperfect manufacture than to the use of improper constituents.

CHAPTER II.

PHYSICAL TESTS OF CEMENTS.

The mechanical operations attending the manufacture of cement, such as the mixing, burning and grinding of the raw materials, bear intimate relation to the final physical properties of the cement, and should be analyzed just as closely as the chemical compositions; but in this treatise it is out of place to discuss manufacturing operations. The manufacture of a cement is therefore to be assumed correct if a sample of it passes those physical tests which are made for the purpose of determining its acceptance or rejectance for use. These tests are of such a character that the results of all experimenters are comparable; but it is not necessary, although it is desirable, that these tests should furnish values of the strength of the material, values which might be used in designing engineering work.

Art. 3.—Commercial Physical Tests.

The physical tests require but brief explanation, and only those tests which are practiced in the United States need consideration. They are five in number:

1. Specific gravity,
2. Fineness,
3. The time of setting,
4. The tensile strength, and
5. The constancy of volume.

They are fully explained in the reports presented on January 21, 1903, and on January 20, 1904, to the American Society of Civil Engineers by its Committee on "Uniform Tests of Cements." A copy of these reports is given in the appendix.

Experience has shown that good cements furnish certain re-

sults in these standard tests, and it is to be expected that, if new cements fulfill the same conditions, their behavior in construction work will be the same.

Art. 4.—Specific Gravity Tests.

As stated in the first of the two reports mentioned above, the specific gravity of a cement is lowered by underburning, adulteration and hydration; but the adulteration must be in considerable quantity to affect the result appreciably. When properly made, this test affords a quick check for underburning or adulteration.

Table I. exhibits the values of the specific gravity of representative Portland and natural cements, and is taken from the Watertown Arsenal Report on "Tests of Metals" for 1901. The determinations were made with a Schumann volumeter, benzine being the liquid employed.

TABLE I.

Brand	Specific Gravity
Alpha Portland Cement	3.11
Atlas Portland	3.09
Storm King Portland	3.07
Whitehall Portland (14 days after grinding)	3.13
Alsen Portland	3.08
Dyckerhoff Portland	3.11
Josson Portland	3.04
Bonneville Improved Natural Cement	2.85
Hoffman Natural	3.06
Norton Natural	3.03
Austin Natural	3.15
Mankato Natural	2.93
Newark & Rosendale Natural (12 days after grinding)	3.06
Obelisk Natural	3.12
Potomac Natural	2.94

It will be seen that Portland cements give uniform results, the average of seven cements being 3.09.

The specific gravity of the above cements after they had set was obtained in various ways.

Table II. shows the specific gravity of the reground material after the cement had set for a period of three days. Different

The specific gravity of the hydrated material in a cake of cement was also determined, as shown in Table III. The material was weighed both in air and in water by means of a chemical balance, account being taken of the water absorbed when the cement was immersed, thus making the necessary correction for voids. The cakes of material in this case were halves of tensile briquettes, but the report does not give the age of the briquettes; there seems to be no difference in the values of those briquettes which set in air or in water.

TABLE III.

Brand	Specific Gravity of Briquettes Which Set In	
	Air	Water
Alpha Portland	2.23	2.29
Dyckerhoff Portland	2.11	2.07
Bonneville Improved-Natural	1.65	1.66
Hoffman Natural	1.79	1.77
Mankato Natural	1.65	1.66
Atlas Portland (Material from 12 inch Cubes)	——	1.92 to 2.17

It will be seen that the specific gravity of the cement after setting is considerably less than the cement before the addition of water.

Article 5.—Fineness Test.

The fineness of a cement indicates to a great degree the proportion of inert material in it. Until lately it has been thought sufficient to measure the fineness of a cement with a No. 100 sieve, but it is now becoming the practice to use a No. 200 sieve.

As recommended by the American Society of Civil Engine these sieves should be made of woven cloth of brass wire wl has the following diameters:

No. 100.................... 0.0045 inches
No. 200.................... 0.0024 inches

The mesh should be regular in spacing and be within the foll ing limits:

No. 100.................... 96 to 100 meshes to the linear inch
No. 200.................... 188 to 200 meshes to the linear inch

The sifting is continued upon a sample until not more tl one-tenth of 1 per cent. passes through after one minute of c tinuous sifting. The percentage sifting through is found weighing the residue and subtracting from the original quant

There is naturally a commercial limit to the fineness of gri ing of a cement; the following tables show characteristic rest obtained from various well known brands of Portland and natu cements.

Table I. is taken from the Report of the Watertown Arse "Test of Metals," etc., 1901; chemical analyses made on the c ferent sized particles of these brands show substantially the sa composition which was found in the material taken from t barrels.

TABLE I.

Brand of Cement	Size of Grain				
	Greater Than .0058 Inch	.0050	.0034	.0027	Smaller Tl .0027
	Corresponding to Sieve Having Meshes—				
	98 x 100	112 x 118	155 x 170	188 x 198	
Atlas Portland........	11.2	3.8	9.1	6.6	69.3
Star Portland.........	12.9	4.7	10.4	11.4	60.6
Alsen Portland........	19.3	5.7	7.9	8.2	58.9
Hoffman Natural......	14.1	1.9	6.4	12.5	65.1
Mankato Natural......	33.6	—	—	23.8	42.6
Norton Natural.......	12.5	—	—	17.5	70.0

Table II. is taken from Vol. VI. of "Mineral Industry," ar covers Portland cements only.

TABLE II.

Brand.	Percentage Passing Sieve—		
	No. 50	No. 100	No. 200
Saylor's	100	96.4	——
Giant	99	94.9	——
Atlas	99.5	92.7	——
Alpha	99.7	94.8	——
Vulcanite	99.6	95.3	——
Sandusky	99.6	92.8	——
Brooks, Shoobridge & Co.	98.8	88.3	——
Alsen	99.7	92.4	68.4
Aalborg	100	99.6	72.0
Condor	99.6	88.5	——

As a matter of present day interest, the following test of the Edison Portland Cement Company's cement, from the same report previously mentioned, may be noted:

Passed No. 100 sieve.................. 99.8%
Passed No. 200 sieve.................. 91.6%

Although two cements may furnish the same degree of fineness as to a No. 100 sieve, finer sieves may show different results. German experimenters have therefore employed the velocities and carrying capacities of liquids as a measure of fineness, but such refinement in testing is unnecessary. The No. 200 sieve furnishes a sufficient test.

The tests which have been made upon cements to prove the superiority of fine grinding are not of great importance, and even in some cases show contradictory results. These are, however, easily explained. Neat unsifted cement, for instance, may show greater strength than the finely sifted, because the grains in the mixture may be better balanced, or because the coarser material, which is the harder burned, and usually the better, has been excluded from the sifted. In the case of mortars the proportions and balancing of the sand greatly outweigh any results that may be obtained due to the sifting of the cement itself. The reader is, however, referred to experiments by Grant, Vol. XXI., Proc. Inst. Civ. Eng., and to Clarke, Trans. Am. Soc. C. E., Vol. XIV.

Art. 6.—Test for Time of Setting.

Two periods are noted in determining the time of setting of a cement: the initial setting, when the material first begins to set,

and the final setting, when the material has acquired a certain degree of hardness. The former period determines the beginning of the process of crystallization, and is important to determine, as a disturbance of the cement after the time of this initial setting produces loss of strength; but the time of setting never furnishes a gauge as to the ultimate strength of a cement.

It is unnecessary to describe the apparatus used in this test; the report of the Committee of the American Society of Civil Engineers records in detail the methods of operation.

Table I., taken from the Watertown Arsenal Report, 1901, shows some characteristic results of the time of setting of some standard American cements, when gauged with different percentages of water; the tests were made according to both American and German standards. The differences for the varying percentages of water are quite marked, the time of set increasing with the amount of water. There is also considerable difference in the results of the two methods of test. In general, it may be said that natural cements set faster than Portland.

TABLE I.

Brand	Water	Gillmore's Method				German Method			
	Per Cent.	Initial Set		Final Set		Initial Set		Final Set	
		H.	M.	H.	M.	H.	M.	H.	M.
Alpha Portland)	20	2	20	5	00	0	35	4	25
	25	3	20	7	30	2	50	6	35
	30	5	40	——		4	40	8	40
Atlas (Portland)	20	4	05	7	10	2	45	6	10
	25	5	10	8	05	3	35	7	05
	30	7	00	——		5	30	——	
Hoffman (Natural)	30	2	15	3	25	1	25	2	55
	35	2	55	5	40	2	20	4	10
	40	3	43	——		2	48	——	
Newark and Rosendale (Natural)	35	0	37	1	17	0	32	1	07
	40	0	47	3	44	0	40	2	19
	45	1	08	4	18	0	48	3	33

Action of Plaster of Paris—The time of setting of a cement may be delayed by the addition of a small percentage of plaster of Paris. The action in that case is merely mechanical. The plaster of Paris dissolves in the water and forms a protecting covering about the cement particles; at the same time it hardens

and prevents action of the water on the cement. In small percentages, plaster of Paris is found to increase the strength of cements, but in large quantities expansion or blowing of the cement is likely to occur. The action in that case is similar to that of sea-water on cement.

E. S. Wheeler, on page 2938 of the Report of the Chief of Engineers, U. S. Army, for 1895, records numerous tests showing the effect of plaster of Paris on the time of setting. An addition up to 2 per cent. increases both the periods of initial and final set, but an addition of more than 2 and up to 10 per cent. decreases this period. It is not necessary to give the detailed figures of these experiments.

Table II. is taken from the Report of the Chief of Engineers, U. S. Army, for 1896, p. 2832, and shows the varying values of

TABLE II.

Tensile Strength of Portland Cement with Varying Percentages of Plaster of Paris. The sand is natural Point aux Pins. Each result is an average of five specimens.

Plaster of Paris to Total Cement	Ratio of Cement to Sand	Strength in Lbs. Per Sq. Inch at Age of—		
		7 Days	6 Months	1 Year
0 per cent.	1:0	487	743	——
1 per cent.	1:0	626	746	——
2 per cent.	1:0	600	754	——
3 per cent.	1:0	519	742	——
6 per cent.	1:0	380	660	——
0 per cent.	1:2	323	492	487
1 per cent.	1;2	388	530	515
2 per cent.	1:2	360	547	610
3 per cent.	1:2	289	607	588
6 per cent.	1:2	192	663	647

the tensile strength of a Portland cement with the addition of various percentages of plaster of Paris. It will be seen in general that an addition of plaster of Paris up to 2 per cent. has no weakening effect. This is shown both for neat cement and for a cement mortar of 1 part of cement to 2 of sand. Again, it will be seen that the mortar in which the cement contained a large amount of plaster of Paris attained considerable strength at the age of one year. The report noted records tests on three brands of Portland cements and on some natural cements; the results

are similar to those in the table; but many of the natural cements checked and disintegrated before the time of testing. The effect of the addition is seen to give very variable results, but a safe limit is 2 per cent.

The time of setting of a cement depends also on its chemical composition and on the character of its burning. In general, a lightly burned cement sets quicker, as does also a freshly burned cement; but there are frequent exceptions. The quantity of water used in gauging the cement, the temperature of the water and the temperature of the air all affect the time of setting. A rise of temperature follows the setting of all cements, and this rise increases very rapidly for fast setting cements. The time of setting is also affected by the volume of cement mixed.

TABLE III.

Compressive Strength in Pounds per Square Inch when regauged after an interval of—	Brand							
Hours After First Mixing	Alpha Portland	Dyckerhoff Portland	Star Portland	Storm King Portland	Josson Portland	Austin Natural	Bonneville Natural	Norton Natural
0	7279	3549	3489	1792	3328	719	895	713
1	—	3667	—	—	—	—	—	—
2	6169	3412	3737	1599	3498	724	387	443
3	—	—	—	—	—	—	—	—
4	7146	3402	3753	1495	3827	340	388	340
6	6774	2686	3903	1151	3696	276	*425	424
8	6539	2439	3889	—	—	—	—	378
10	—	2312	—	—	—	—	—	—
12	—	1898	—	—	—	—	—	—
14	—	1745	—	—	—	—	—	—
16	—	1758	—	—	—	—	—	—
18	—	1666	—	—	—	—	—	—
20	—	1690	—	—	—	—	—	—

*After seven hours.

Temperature Affects Setting—Gen. Gillmore, in his Treatise on Limes, Mortars and Cements, page 83, shows some interesting results as to the variations in time of setting due to changes of temperature of water used in mixing. It is unnecessary to reproduce here his results, but he shows that invariably high temperatures increase the rapidity of setting. There may be marked differences in the variations for different cements, but the state-

ment is true of all. Exactly similar results are recorded by E. S. Wheeler in the Report of the Chief of Engineers, U. S. Army, 1895, page 2936.

Retarding the Set—If agitated sufficiently, it is possible to prevent a cement from setting at all; if disturbed after the final setting has commenced, its strength is greatly decreased, and since natural cements, as a class, reach their final set in periods of time considerably less than Portland cements, it may be expected that the effect of regauging the natural cements is of greater consequence. This is clearly shown by Table III., which is taken

TABLE IV.

Ult. Compressive Strength in Pounds per Square Inch after elapse of X hours between initial mixing and placing of material in moulds	Brand of Cement		Ult. Compressive Strength in Pounds per Square Inch after elapse of X hours between initial mixing and placing of material in moulds	Brand of Cement	
Hours	Star Portland With Plaster	Star Portland Without Plaster	Hours	Star Portland With Plaster	Star Pertland Without Plaster
0	5467	2414	24	1669	1462
1	4665	2594	30	1442	1216
2	6421	2561	36	1279	1101
4	5470	2167	42	1132	1143
6	2718	2282	50	1168	1069
8	2662	2021	60	1150	1110
10	2387	1842	70	1001	849
12	2160	1541	80	763	834
14	2214	1242	90	723	782
16	2154	1426	100	681	737
20	1901	1499			

from the Watertown Arsenal Report for 1901, and exhibits the results obtained in retarding the setting of cements which, after having been mixed with water, were left undisturbed until each of the periods shown, when a sample from the main batch was extracted.

The majority of these specimens were 6 inch cubes, although some were smaller sized cubes. Many of the results obtained were averages of two or more samples, and the average age of the specimens was about thirty days. In this set of experiments the main batch of the cement was left undisturbed until the sam-

ples were extracted, when the entire mass was again gauged with water; the sample was then tamped into a mould and allowed to set without further interference.

Table IV. shows the compressive strengths attained when the main batch of the cement was not left undisturbed after the initial mixing, but kept in a continual state of agitation in the mixing bed. In this test the two kinds of cement used were both Star Portland, but one contained plaster of Paris, as a restrainer to control the time of setting, while the other contained no plaster. The effect of the restrainer is clearly shown.

TABLE V.

Brand of Cement	Percentage of Water	Maximum Temperature in Degrees Centigrade	Ultimate Compressive Resistance in Pounds per Sq. Inch	Age in Days	Weight per Cu. Ft. in Lbs.
Alpha Portland.......	26.2	95.	5706*	9	133.4
Star Portland.........	26.5	76.	—	—	—
Storm King Portland..	27.0	42.5	—	—	—
Whitehall Portland....	25.2	103.5	—	—	—
Dyckerhoff Portland..	25.0	63.	1547	13	130.9
Josson Portland.......	29.7	51.	—	—	—
Atlas Portland........	22.7	81.5	4872	9	137.5
Bonneville Natural....	37.6	39.5	—	—	—
Obelisk Natural.......	35.0	37.5	840	13	116.7
Hoffman Natural.......	36.5	34.0	349	8	115.1
Austin Natural........	40.0	35.0	—	—	—
Mankato Natural.......	44.6	40.0	—	—	—
Norton Natural........	41.8	39.0	—	—	—

*Not ruptured.

Temperature Changes During Setting—Table V. shows the temperatures acquired by cements during setting; these values have been abstracted from the Watertown Arsenal Report for 1901. Experiments were made on 12-inch cubes, the upper surface being exposed to the air. The thermometer bulbs reached to the centre of the cubes. It is interesting to note that the highest temperatures were reached by Portland cements as a class, in some cases exceeding the boiling point of water. A number of hours elapsed before the maximum temperature was obtained, generally six to twelve hours for a neat Portland cement, while a 1:1 mortar required about eighteen hours. At the end of one and one-half days the Portland cements still remained

above the temperature of the room, but the natural cements had nearly returned to the temperature of the room. The cements which reached the highest temperatures almost invariably showed the sharpest crests in the curves which were plotted with the times and temperatures as ordinates.

It is probably merely a matter of coincidence that the highest temperatures belonged to cements showing the highest ultimate compressive resistance, but it may be interesting to investigate this point more fully at some future time. The difference between the Portland and natural cements is very marked, but may be due partly to the excess of water used in mixing the samples.

Temperature changes are naturally less marked when a cement is mixed with sand and stone than when neat, but they are still very noticeable. Experiments regarding these changes are now in progress on some large pieces of concrete work, but the results are not yet public.

Art. 7.—Tests of Tensile Strength.

The test of the tensile strength of a cement is the decisive test in regard to its acceptance for use, even though in the majority of building operations it is not the tensile strength, but the crushing strength of the material, which is desired. It may be shown, however, that these two resistances bear an almost fixed ratio to one another, and since the tensile tests are more easily made and require less expensive apparatus, they have practically displaced the crushing tests.

The tests are made on small briquettes of standard form whose minimum area of cross-section is one square inch; these briquettes are formed both from the neat cement and from mixtures of the cement with various percentages of standard or normal sand, and they are tested at stated periods after making. The periods are usually one, seven and twenty-eight days.

The tests which are made to determine the tensile strength of cement have often been criticised on account of the poor form of cross-section of the briquette, and on account of the use of a class of sand which is never employed in practice. Although erroneous values of the actual strength of the cement in working prac-

TENSION EXPERIMENTS

Age	1 Cement 0 Sand Immersed	1 Cement 0 Sand Not Immersed	1 Cement 3 Sand Immersed	1 Cement 3 Sand Not Immersed	1 Cement 5 Sand Immersed	1 Cement 5 Sand Not Immersed
	Ultimate Resistance in Pounds per Square Foot.					
7 days.........	515	642	277	301	127	131
28 days........	658	651	350	438	180	247
84 days........	697	600	457	538	233	335
6 months......	814	638	487	605	281	410
I year.........	765	575	550	703	271	442
2 years........	838	507	503	650	270	408
Gauged with ...	23%		10.1%		9.5% water	
COMPRESSION EXPERIMENTS						
7 days.........	6320	6200	2570	2930	1210	1260
28 days........	8400	8050	3520	4360	1560	1960
84 days........	11200	9700	5100	5750	1910	3310
6 months......	13000	12200	5280	6160	2150	3200
I year.........	14180	14200	6520	7720	2150	3560
2 years........	14700	14800	6000	7100	2450	3500

Table I. shows the results of two sets of experiments made at the Laboratory de l'École des Ponts et Chaussées, under date of February 6, 1896, and published by Berger & Guillerme in "Ciment Armé." The values given are all the mean of five or six specimens.

In the first series of experiments the briquettes were exposed to damp air for twenty-four hours and then immersed in fresh water; in the second series there was no immersion. The cross-

*See *Appendix*.

section of the specimens varied from 0.78 to 1.2 square inches. The lower part of the table is inserted to show the ratio between tensile and compressive stresses for mixtures of the same kind.

Figure 1 was plotted from results published by E. C. Clarke, in Vol. XIV., 1885, of the Transactions of the American Society of Civil Engineers, and shows the strength obtained by Portland and natural cement and mortar briquettes whose minimum area of cross-section was $2\frac{1}{4}$ square inches. Twenty different brands

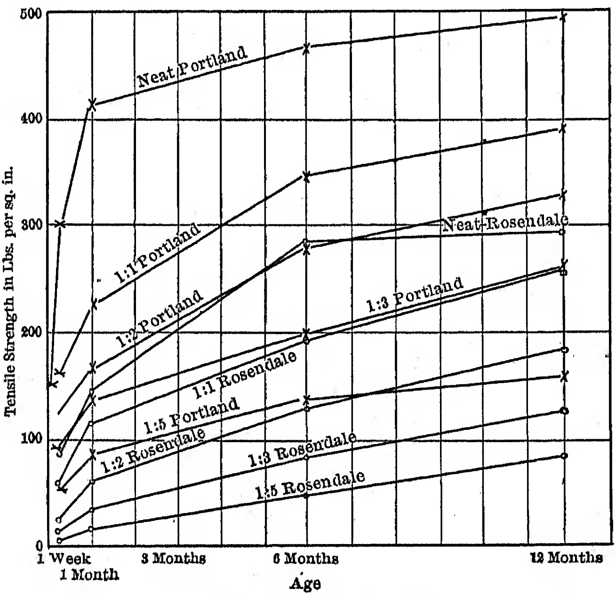


FIG. 1.—CLARKE'S TESTS.

of cement were used, and the figure represents 25,000 breakings. The ordinary cement briquette has a minimum area of 1 square inch, but comparative tests made at the time showed little difference in result between cross-sections of 1 and $2\frac{1}{4}$ square inches.

Figure 2 shows the results obtained in tensile tests on four brands of Portland cement, as published in the report for 1895 of M. L. Holman, Water Commissioner of St. Louis; each plotted point represents an average of ten briquettes. The briquettes were all 1 cement to 3 normal sand and were left one day in air

and the remainder of the time in water. The figure shows a continual increase in the strength of the briquettes for the period

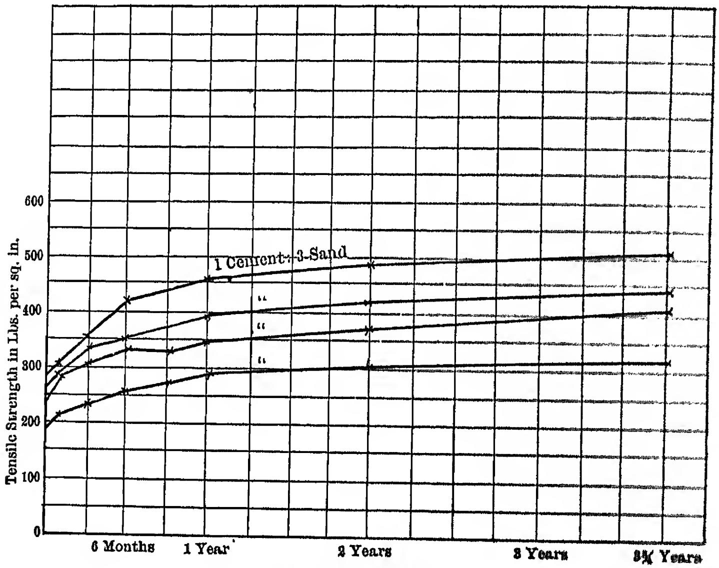


FIG. 2.—HOLMAN'S TESTS.

of $3\frac{3}{4}$ years shown; but a similar series of tests made upon neat cement briquettes showed a slight decrease after the end of one

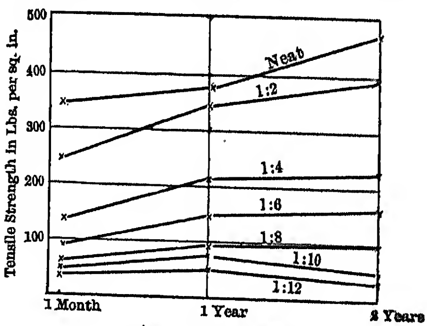


FIG. 3.—CLARKE'S TESTS.

year, the greatest decrease, as compared to the maximum strength obtained, being about 20 per cent. It is only proper to note that

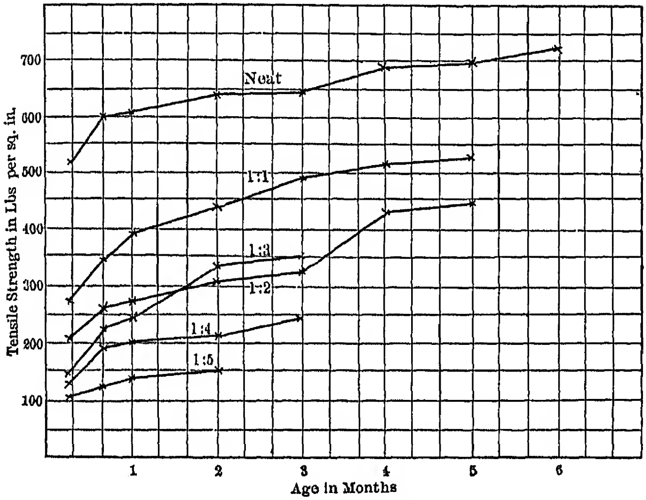


FIG. 4.—RAFTER'S TESTS.

briquettes, when one year old or over, become very brittle and may show erratic results in the testing machine.

Figure 3 shows the results obtained by E. C. Clarke, as part of the same experiments mentioned previously, in which he found the variation in the strength of cements when mixed with increased proportions of sand. These tests were all made on one single brand of cement and represented 500 breakings.

Figure 4 shows the strength attained by a Portland cement both at various ages and when mixed with different volumes of sand. Each point marked on the curves represents an average of five briquettes. These tests were made by Mr.

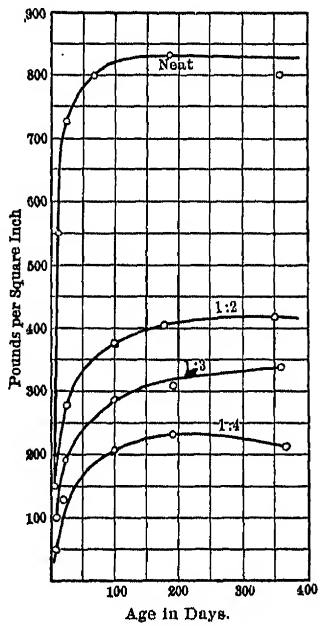


FIG. 5.

George W. Rafter and are published in the annual report of the "State Engineer of New York" for 1894.

Figure 5 is taken from Johnson's "Materials of Construction," page 575, and shows the average tensile strength acquired at various ages by many samples of one brand of American Portland cement, as reported by Messrs. R. W. Hunt & Co.

R. W. Lesley published in the Journal of the Association of Engineering Societies, 1895, the results of long time tests made on samples of cement representing 300,000 barrels of the Giant

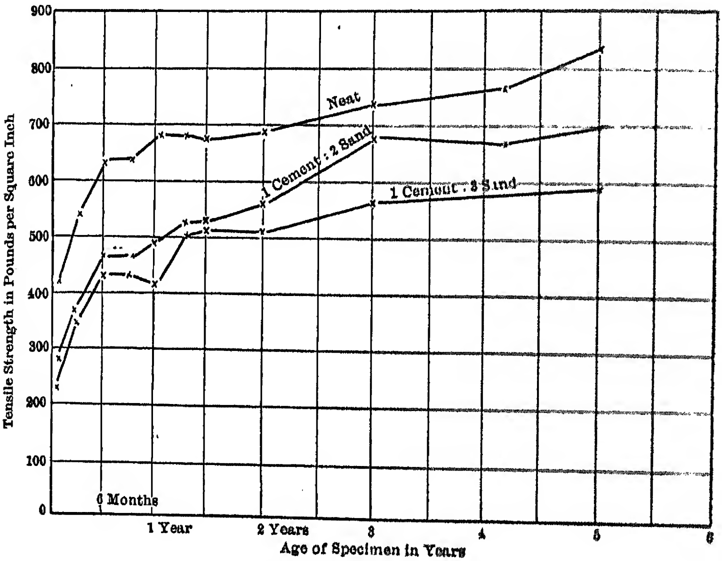


FIG. 6.—LESLEY'S TESTS.

Portland brand of cement. Figure 6 is plotted from these results, and represents a series of tests made on 50,000 barrels of cement used on the Sodom and Bog Brook dams of the New York aqueduct. The results there shown are characteristic of the entire series. Each point plotted is an average of 1,000 to 1,300 briquettes. Taking only the tests made on briquettes of one cement to three sand, it will be seen that the strength at three months and six months, as compared to five years, are respectively 60 per

cent. and 73 per cent.; and for three months and six months, as compared to one year, respectively 82 per cent. and 100 per cent.

Figure 7 shows the results of experiments recorded by J. Grant in the Proceedings of the Institution of Civil Engineers, Vol. XXXII., page 280, and shows the variation in the tensile strength of Portland cement briquettes from observations extending over a considerable number of years. The form of specimen used was not the standard form as used to-day, the minimum area of cross-section being 2¼ square inches. The specimens were all kept in water from the time of making until the time of testing, and ten specimens were tested at each age. It will be

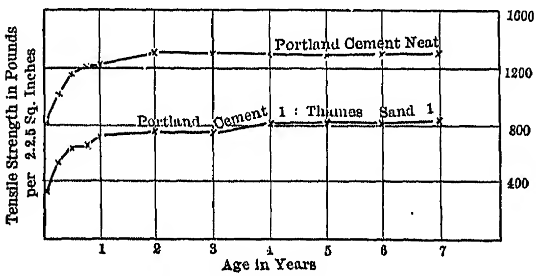


FIG. 7.—GRANT'S TESTS.

seen that there is no increase of strength after two years. For neat specimens the percentage of increase gained after three months' age is 20 per cent., as compared to the final strength; and for the one cement to one sand mortar the corresponding percentage is 33. Similarly, comparing the increase in strength after six months to the final strength, these percentages become respectively 11 and 22.

The following table shows the tensile strength of the Edison Portland Cement Company's cement, and is inserted as a matter of interest as giving the tensile resistance of the latest cement on the American market; the tests are taken from the report already mentioned.

Neat,	1 day =325 lbs. per sq. in.	Average of 5 specimens.
Neat,	7 days=676 lbs. per sq. in.	" " "
1:3,	7 days=255 lbs. per sq. in.	" " "
1:3,	28 days=331 lbs. per sq. in.	" " "

that it will make no sensible difference in tests of cement mixtures when the age of the specimen is in the neighborhood of three months. The results so obtained need no correction for age and will all be comparable.

It is of interest to record the following empirical formula which has been proposed by W. C. Unwin (Proc. Inst. Civ. Eng., Vol. LXXXIV.) for determining the tensile strength of a briquette within two years after making; he derived it by analyzing the results of tests by Bauschinger, Grant, Clarke and others.

If y is the strength of a cement or mortar at x weeks after mixing, and a the strength of the same in pounds per square inch at seven days, then

$$y = a + b\ (x - 1)^n$$

The constant n has values which can be assigned beforehand, and the constant b is determined by experiment on pieces more than one week old. Unwin, assuming for the case of tension n to be $\frac{1}{2}$, finds that b varies within rather narrow limits.

Art. 8.—Ratio of Compressive and Tensile Strengths.

The ratio of compressive and tensile strength is not a constant quantity for all ages of a mortar, since, in general, compressive strength increases faster than the tensile strength; but experiments show that the variation of this ratio is not very great.

J. B. Johnson in "Materials of Construction" analyzes the results of numerous experiments on a mortar of one cement to three sand, which were recorded by Tetmajer in his "Communications," Vol. VI., and expresses the ratio between these strengths by the following equation:

$$R = 8.64 + 1.8 \log A$$

where R represents the ratio between the compressive strength

and the tensile strength, and A is the age of the cement mortar in months.

Büsing and Schumann, in "Der Portland Cement," 1899, present in Table I. results which furnish the relations between these two kinds of stress. The specimens were made with ordinary sand and gauged with different percentages of water, and were

TABLE I.

Age in Days.	10 Per Cent. Water			12 per Cent. Water			15 per Cent. Water		
	Pounds per Sq. In.		Ratio	Pounds per Sq. In.		Ratio	Pounds per Sq. In.		Ratio
	Tension	Compression		Tension	Compression		Tension	Compression	
7.....	284	2860	10.1	196	1550	7.8	143	781	5.4
28.....	370	4050	10.9	326	2270	7.0	260	1420	5.5
90.....	407	5050	12.4	366	2940	8.0	328	2130	6.5
180.....	456	5400	11.8	380	3200	8.4	321	2410	7.5

tested at various ages. It is to be noted that with the increase of water the compression decreases faster than the tension, and that with the increase of age the compression tends to resume its former relations.

TABLE II.

Age in Weeks	Mixture	Tension		Compression		Bending		Shear	
		Ult. Resistance Pounds per Square Inch		Ult. Resistance Pounds per Square Inch		Extreme Fibre Stress in Lbs. per Sq. Inch		Ult. Resistance Pounds per Square Inch	
		Specimens Hardened in							
		Air	Water	Air	Water	Air	Water	Air	Water
1.........	1:0	231	224	1860	1910	695	625	276	271
	1:3	106	95	920	880	273	247	109	116
	1:5	68	64	543	537	168	158	81	77
4.........	1:0	266	294	2460	2490	860	887	316	346
	1:3	148	169	1500	1040	392	381	182	181
	1:5	119	103	962	977	284	276	136	131
104 to 113.	1:0	257	292	3400	4680	1010	1350	388	415
	1:3	244	272	2080	3340	748	973	294	375
	1:5	177	232	1510	2960	545	810	248	364

An exceedingly interesting set of experiments was published as long ago as 1879, by Bauschinger, in the Proceedings of the Munich Technical Institute. Bauschinger experimented on mortar specimens of 1 cement to 0 sand, 1 cement to 3 sand, and 1 ce-

of 16.02 was exceptional, the next highest ratio being 12.76. The limits of the ratios of the ultimate fibre stress in flexure to maximum tensile stress were 3.93 to 2.46 for the dry, and 4.65 to 2.25 for the wet. The limits of the ratios between shear and tension were 1.51 to 1.03 and 1.57 to 1.07 for the dry and wet respectively.

TABLE III.

Age in Air. Days.	Age in Water. Days.	Gauged with 20 per Cent. Water: Compressive Strength in Lbs. per Sq. In.	Tensile Strength in Lbs. per Sq. In.	Ratio	Gauged with 22 per Cent. Water: Compressive Strength in Lbs. per Sq. In.	Tensile Strength in Lbs. per Sq. In.	Ratio	Gauged with 25 per Cent. Water: Compressive Strength in Lbs. per Sq. In.	Tensile Strength in Lbs. per Sq. In.	Ratio
1.....	——	717	196	3.7	595	189	3.1	430	190	2.3
7.....	——	3040	354	8.6	3260	392	8.3	2610	402	6.5
28.....	——	3990	566	7.1	3760	457	8.2	3130	450	7.0
1.....	6	4250	780	5.5	4720	666	5.8	3880	329	11.8
1.....	27	7370	906	8.1	6870	866	7.9	7580	758	10.0

Table III. furnishes values of the ratio between tensile and compressive stresses, and is taken from the Watertown Arsenal Report for 1902. The specimens were all of neat Peninsular Portland cement. Ten specimens of each kind were tested, with varying percentages of water and at different ages. The ratios of the two kinds of stress are given in the table. The tensile specimens were of the standard form; although not so stated, it is probable that the crushing tests were made on the broken halves of the tensile specimens.

Reviewing all these experiments, it is seen that it will never be far from wrong to assume the ratio between ultimate compression and tensile resistances as about 10; although it should be noted that all the tensile tests were made on specimens of a form which probably give too high values.

Art. 9.—Variations in the Making of Tensile Tests.

The author does not believe it to be of any importance to consider in any detail questions bearing on variations in the manner of making tensile tests. Under this heading may be included the variation in the rate of loading a specimen; the testing of a specimen, either dry or wet, or an appreciable length of time after taken from the storage tanks; the variations in the strength due to mixing with different percentages of water; the effect of temperature changes of the water in the immersing tanks; the effect of salt water in these tanks; the period elapsing before placing the briquettes in water after making, whether twenty-four hours or immediately upon setting hard; the methods of filling the moulds, whether by ramming or by slightly tamping; the time employed in mixing the materials in the dry state or in the wet state; the eccentricity of a specimen in the clips of the testing machine; the filling of the molds with dry cement, and then adding water, etc.

The results of the tensile tests are made simply a basis of comparison for accepting or rejecting offered cements, and although the questions noted do affect the results appreciably, under standard conditions of making, the personal equation of the operator will be a factor of greater importance than anything else. Certain points depending on comparative results may, however, be determined in the tensile tests of briquettes, of which the following is the most important, namely, the advantages to be gained by the use of one of several possible sands. A choice between different sands offered may be determined by these tensile tests, and this question frequently arises in building operations. In this connection there has lately been much question concerning the suitability of rock screenings for use in place of sand.

Art. 10.—Variations of Sands in Tensile Tests.

The following experiments, reported by E. S. Wheeler in the Report of the Chief of Engineers, U. S. Army, for 1894, page 2321, bear directly upon this point. Table I. shows the mean tensile strength attained by various mixtures of natural sand, of the standard sand used for testing and of various rock screenings with natural cements; each result shown is an average of five to ten specimens, all briquettes being one cement to three sand. The sands were all brought to the same degree of fineness by sifting and remixing, there being used, in all cases, excepting for the standard sand, 25 per cent. each of sand retained between sieves Nos. 20 to 30, 30 to 40, 40 to 50 and 50 to 80. The superiority of the mixtures formed from screenings obtained from crushed limestone and sandstone is clearly shown. The table is for natural cements only; but Portland cements furnished exactly similar results.

TABLE I.

Kind of Sand	Mean Tensile Strength in Lbs. Per Square Inch at Age of			
	28 Days	6 Months	1 Year	2 Years
Crushed Quartz	117	344	356	332
Point aux Pins Natural Sand	93	297	339	308
Limestone Screenings	162	467	526	601
Sandstone Screenings	113	316	416	462
Standard Sand	118	330	342	324

The same experimenter records on page 2806 of the Report of the Chief of Engineers, U. S. Army, for 1896, experiments made in determining the tensile resistance of briquettes when mixed with natural sand of varying fineness. The sand was Point aux Pins, and each result in Table II. is an average of five briquettes, the briquettes being one cement to two sand. Portland cement was used. The exponents of the letters C, M, F and V show the percentages of each fineness used, C being the material passing the No. 10 sieve, V passing the No. 40 sieve, M being the material retained between the 20 to 30 sieves, and F between the 30 to 40 sieves. The results obtained are very interesting. They show that the mortar in which the sand contains the greatest

M^1 F^2 V^1	271	366	456	438
			18 Months	3 Years
C^5 M^{20} F^{45} V^{30}	——	566	581	632
C^5 M^{20} F^{40} V^{35}	——	544	592	622
C^5 M^{15} F^{35} V^{45}	——	551	585	587
C^5 M^{15} F^{30} V^{50}	——	528	589	629
C^5 M^{10} F^{25} V^{60}	——	540	593	622

Exponents of letters C, M, F, V show numbers of parts of each degree of fineness used; C passes No. 10 sieve; M, between Nos. 20 to 30; F, between Nos. 30 to 40; V passes No. 40.

Figure 1 is taken from tests reported by R. Feret in the "Annales des Ponts et Chaussées," 1892, and shows the ultimate compressive resistance attained by various mortars mixed with vari-

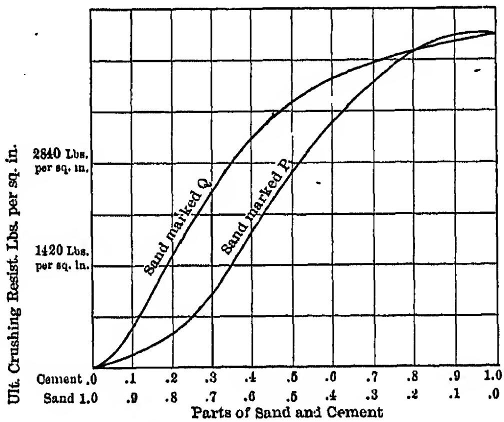


FIG. 1.—FERET'S TESTS.

ous proportions of the same cement to two kinds of sand, the relations varying from neat to 1:9. The specimens were immersed two months in sea water, and two kinds of sand were

used—one, which was marked "Q," was very coarse sand; the other, marked "P," very fine. It will be seen that the coarse sand gave uniformly higher resistance than the fine.

Table III. is taken from a paper by E. S. Larned, presented before the American Society for Testing Materials, 1903, and shows the tensile strength of cement mortar with sand grains of different diameters. Each result shown is an average of six briquettes. The table gives only the results for Giant Portland cement mortar, one part cement to two of sand by weight, but the

TABLE III.

Percentage of Sand Used				Ultimate Tensile Strength at the Age of		
No. 30	No. 20	No. 100	Fine	7 Days	28 Days	6 Months
100	—	—	—	286	288	412
—	100	—	—	294	331	473
—	—	100	—	201	226	294
—	—	—	100	129	159	223
80	10	10	—	361	380	486
70	15	12½	2½	301	303	428
60	20	15	5	307	311	419
50	25	17½	7½	391	400	538
40	30	20	10	350	355	475
30	25	30	15	362	359	478
20	20	40	20	317	374	480
10	15	50	25	291	354	488
50	—	—	50	247	287	351
50	50	—	—	440	408	542
50	—	50	—	309	336	438
25	25	25	25	279	337	447
40	Crushed —	Quartz 60	—	257	331	3 Months 351

Natural sand used: first passed through No. 8 screen and residue excluded; No. 30 sand passed No. 20 screen and caught on No. 30 screen; No. 20 sand passed No. 8 screen and caught on No. 20 screen; No. 100 sand passed No. 30 screen and caught on No. 100 screen. Fine is clean white sand sifted through No. 100 screen.

original paper shows similar results with tests upon two natural cements. All the briquettes were gauged with the same percentage of water. It will again be noticed that those briquettes in which the sand is composed of varying percentages of the different kinds show uniformly greater strength than those briquettes formed of one kind of sand only. In those briquettes in which one grade of fineness of sand only is used the coarsest sand shows the highest ultimate strength.

gave the highest ultimate tensile resistance, and that the granite, quartz and mica mixtures furnished values considerably less. The actual values obtained by these mixtures are not of much importance; but it is interesting to record Feret's results on marble, since they substantiate the claim that a calcareous stone yields stronger concretes than a quartz or granite stone.

TABLE IV.

Material	Proportion of Sand to Cement by Volume	Ult. Tensile Resistance in Lbs. per Sq. In. at the Age of		
		1 Day	7 Days	28 Days
Cow Bay Sand........	2:1	107	364	530
Fine Screenings.......	2:1	92	330	528
Sand from Reservoir..	2:1	86	175	——
Cow Bay Sand........	3:1	37	228	311
Fine Screenings.......	3:1	39	223	394
Sand from Reservoir...	3:1	29	122	——

In connection with this it is of interest to note that in "Engineering News," May 17, 1890, is given an abstract of results obtained by breaking a large number of cement blocks 3 feet 3½ inches long and 7.9 inches square, the original tests having been recorded in "Wochenschrift des Oester. Ing. Ver." Sufficient details are not provided to permit an analysis of the results as flexure tests, but the following general statement is worth recording: That the strength of specimens made with granite, with clinkers (vitrified brick) and with sandstone varied in the order named, granite showing the greatest strength.

Table IV. is taken from a report made by Mr. A. Black, of the Department of Civil Engineering of Columbia University, to

the Investigating Commission on the Jerome Park Reservoir, 1903, and shows the tensile strength of three kinds of mortars mixed with Atlas Portland cement. The sand for these mixtures was either natural Cow Bay sand, or the natural sand from the site of the Jerome Park Reservoir, or artificial sand composed of rock screenings. Each figure is the average of a large number of briquettes, and it is seen that the briquettes made with the screenings are not inferior to those briquettes made from the natural sand.

Table V. shows the relative strength of sand and stone dust mortars, as determined by T. S. Clarke, and as reported by him in the "Engineering News" of July 24, 1902. In his case, however, the stone dust was very much finer than the sand, and the

TABLE V.

Showing Strength of Sand Mortar Compared with Stone Dust Mortar; Portland Cement; 24 Hours in Air, 6 Days in Water; Amount of Water Used, 10%.

Proportions			Av'ge Tensile Strength, Lbs. per Sq. In.	Average Number of Tests
Cement	Sand	Stone Dust		
1	—	2	245	15
1	2	—	345	16
1	—	3	216	3
1	3	—	241	3

results show that the tensile strength of the natural sand mortar is greater than that of the stone dust mortar. This is to be expected, if the fineness of the two varieties exhibits the difference noted.

Reviewing the preceding experiments, it may be concluded that rock screenings may be substituted for sand, either in mortar or concrete, without any loss of strength resulting. This is important commercially, for it precludes the necessity of screening the dust from crushed rock and avoids, at the same time, the cost of procuring a natural sand to take its place.

Effect of Clay in Sand.—In construction work the question of the presence of fine clay in a natural sand is generally at once disposed of by prohibiting it, but the following data show that this solution is not satisfactory.

G. J. Griesenauer has reported in "Engineering News," April 28, 1904, tests made on the tensile strength of Portland and natural cement mixtures when the sand which was used contained various percentages of clay or loam; also, when the sand was natural dirty sand, just as it came from the sand bank, and

TABLE VI.

Age	Cement 2 Clay 1	Cement 1 Clay 1	Cement 1 Sand 2	Cement 1 Sand 2 Clay 0.2	Cement 1 Sand 2 Clay 0.4	Cement 1 Sand 2 Clay 0.6
1 Week........	185	192	150	197	185	145
1 Month.......	263	271	186	253	245	203
6 Months......	248	322	320	361	368	317
1 Year	303	301	340	367	401	384

when the same was washed. The experiments extended over a considerable period of time.

Two sets of experiments (which it is unnecessary to reproduce here) were made on Portland cement mortars 1:2 and 1:3, in which loam was added to the clean sand in percentages as high even as 20 per cent. The results from those tests show that the clay affected, in almost all cases, the 1:2 mortars adversely, but appeared, on the contrary, to benefit the 1:3 mixtures for almost every percentage of loam added and for all ages. These contradictory results are probably explained by the fact that in the one case the loam helped to balance the mixture, and in the other case not.

Figures 2 and 3, from the same tests, are, however, of greater interest, since they represent more nearly conditions in practice. Figure 2 shows the strength of 1:3 Portland cement mortars

mixed with natural sand taken from various pits and containing the percentages of loam indicated. Figure 3 shows the results obtained on 1:3 mortars in which the sand containing 6 per cent. of loam was first used in its natural condition and then after having been washed.

The results are entirely harmonious. They show that the presence of loam in a 1:3 mortar rarely decreases the ultimate

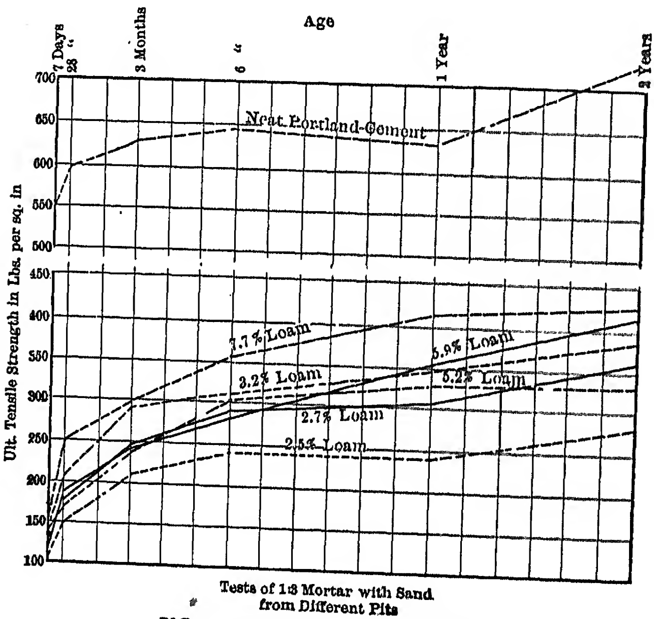


FIG. 2.—TESTS BY GRIESENAUER.

strength. As has already been said, the reason for this is probably to be explained by the better balancing of the mixture. Nothing indicates why this same reasoning may not apply as well to mixtures of cement, sand and stone. If this be the case, there is no reason why a loamy sand should not be used for making concrete.

Professor C. E. Sherman has also recorded in the "Engineering News" of November 19, 1903, an extended series of tests which he had made concerning the effect of clay and loam on cement mortars. The tests were made on the usual form of ten-

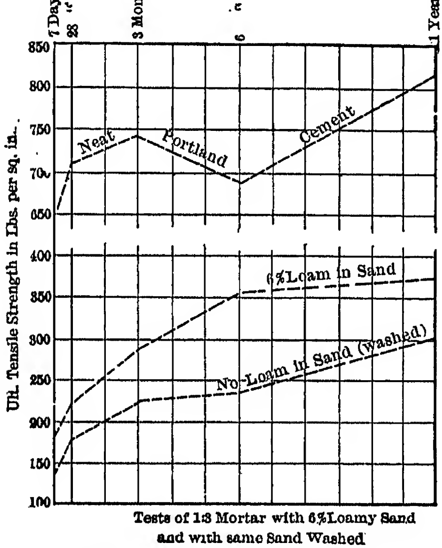


FIG. 3.—TESTS BY GRIESENAUER.

of a mortar composed of sand with clay or loam, fell below the curves representing the tensile strength of the clean sand mortar. And in eight cases out of twelve the 15 per cent. mixtures furnished the very highest results at the end of one year.

Table VII. shows results abstracted by the "Engineering Record," July 16, 1904, from tests describel by Charles M. Mills in a paper read before the Philadelphia Engineers' Club. The tests were made in the laboratory of the Philadelphia Rapid Transit Commission on briquettes of the standard tensile form.

The gravel used in the mortar tests after screening fulfilled the requirements for "coarse sand or gravel, graded from coarse to fine, to reject all particles exceeding ¼ inch in diameter," but it contained a considerable quantity of loam. Tests were made with the natural gravel, with the same screened, and with the same washed, as fully shown in the table, each result being the average of 4 to 6 specimens.

The greatest strength was attained in the crushed rock mixtures, and the lowest strength was given by the standard quartz

TABLE VII.

Material	Percentage of Loam in the Sand	Percentage of Water Used in Mixing	Av. Tensile Strength in Lbs. per Sq. In. 1 Day in Air 6 Days in Water	Av. Tensile Strength in Lbs. per Sq. In. 1 Day in Air 27 Days in Water
A—Neat Portland Cement	——	21	527	862
B—Standard Quartz Sand. 1 Cement to 3 Sand.	——	9.9	175	263
C—Gravel (unwashed, unscreened). 1 Cement to 3 Gravel.	25	11.2	208	316
D—Gravel (washed, unscreened). 1 Cement to 3 Gravel.	3	10.7	230	355
E—Gravel (unwashed, screened). 1 Cement to 3 Gravel.	25.2	13.7	219	335
F—Gravel (washed, screened). 1 Cement to 3 Gravel.	3.2	11.2	211	367
G—Trap Rock Dust. 28% retained on Sieve No. 20. 1 Cement to 3 Grit.	16.4	15.0	213	385
H—Trap Rock Grit. 1 Cement to 3 Grit.	11.4	12.5	282	459
J—Crushed Trap Rock. 1 Cement to 3 Crushed Rock.	——	11.2	279	416
K—Trap Rock Grit and Excavation Gravel (unwashed, screened). 1 Cement, 1½ Grit, 1½ Gravel.	——	12.5	218	372

sand; these results might have been expected. In groups E to F, which contained the loamy gravel, the variation due to the different percentages of loam is seen to be practically negligible; a very slight increase is shown for the clean gravel specimens at the end of 28 days. In the work for which these tests were a preliminary, a mixture of equal parts of crushed trap rock grit and screened gravel was used.

The tests are made on small pats of cement, which may be treated in various ways, such as by immersion in hot water or in cold water or in chemical solutions; after a certain lapse of time they are then examined as to the presence of defects, such as distortion of the specimen or cracks. The hot water or chemical test, however, has never been considered entirely satisfactory, either for the purpose of accepting or rejecting a cement. The failure to pass the hot water test does not necessarily imply rejection; it classes a cement as suspicious, but the appearance of defects in specimens left in cold water for periods of seven to fourteen days does determine its unfitness for use.

It is proper to say, however, that sometimes freshly burned cements, which fail to pass the "cold water" test, may pass the same after some period of "aging"; it is therefore possible that the same cement may be accepted at a later period after having been previously rejected. Quantitative results are not obtained in these tests.

CHAPTER III.

GENERAL PHYSICAL PROPERTIES.

Before treating of the resistance to stress of cement mixtures the following physical properties will be considered:

(a) The change in volume of cement mixtures when setting.
(b) The coefficient of expansion due to temperature changes.
(c) The action of sea water.
(d) The porosity and impermeability of cement mixtures.
(e) The effect of freezing.
(f) The adhesion of iron rods to cement mixtures.
(g) The fatigue of cement mixtures.

Art. 12—Variation in Volume of Cement Mortars in Air and Water.

The general conclusions as to the variation of volume which takes place during the hardening of cement mixtures are practically agreed upon by all experimenters; they have been well stated by Professor G. F. Swain, who made elaborate experiments upon the changes of dimensions during the setting of American cements at the Massachusetts Institute of Technology with the aid of two students. These tests are reported in the Transactions of the American Society of Civil Engineers for July, 1887. Experiments were made upon several brands of natural and of Portland cement. Five-inch cubes were made, both of neat cement and with a mixture of one cement to one sand. In two cases mixtures of one cement and three sand were also made. One specimen of each pair of cubes was left in the air, the other in water. Observations were taken at intervals ranging from one day to twelve weeks, and the following conclusions were reached:

5. The changes are less in mortars containing sand.
6. The changes are less in water than in air.
7. The contraction, at the end of twelve weeks, is

For neat cement............ 0.14% to 0.32%
For one cement to one sand.. 0.08% to 0.17%

8. The expansion, at the end of twelve weeks, is

For neat cement............ 0.04% to 0.25%
For one cement to one sand.. 0.00% to 0.08%

9. The contraction or expansion is essentially the same in all directions.

Professor Bauschinger of Munich reported the results of similar tests in "Mittheilungen aus dem Mechanisch-Technischen Laboratorium" of the Royal Technical Institute of Munich, Vol. VII., and his results confirm those of Professor Swain; his test specimens were cubes 4.72 inches on a side. The following table shows his result:

TABLE I.

Mixture Cement to Sand	Age	Contraction in Per Cent. Hardening in Air	Expansion in Per Cent. Hardening Under Water
Neat	16 weeks	.12 to .34	.01 to .15
1:3	16 weeks	.08 to .15	0 to .02
1:5	16 weeks	.08 to .14	—0.03 to .02

Similarly Mr. John Grant records in Vol. LXII., Proc. Inst. Civ. Eng., the results of his experiments on prisms four inches long and two inches square, hardening only in water. He finds that at the end of a year neat cements, without plaster of Paris,

expand .09 to .21 of 1 per cent., and for one cement to three sand .01 to .06 of 1 per cent. These figures were increased for cements with gypsum.

Dr. C. Schumann, in his book, "Portland Cement," 1899, records the results obtained by him in measuring the increase in volume for specimens 3.9 inches long with a cross-section of .775 sq. in., which were immersed in water for various periods of time. Table II. is abstracted from page 78 of this book; each value shown gives the average percentage of increase in length for ten specimens of each kind:

TABLE II.

Age in Weeks	Neat Specimen	1 Cement 3 Normal Sand
1	.048%	.015
4	.082	.021
13	.104	.024
26	.125	.028
39	.139	.030
52	.146	.033

M. Gary records in the Trans. Am. Soc. Civ. Eng. for October, 1893, the results of some tests by Dr. Tornei, manager of the Stern Portland cement factory; the size of specimen was the same as used by Bauschinger. Table III. is an abstract, being the average of the first six cements there shown.

TABLE III.

Mixture	Age in Days	Percentage of Contraction, Hardening in Air	Percentage of Expansion, Hardening Under Water
Neat	7	.064	.014
	28	.129	.026
	90	.181	.021
1 Cement 3 Sand	7	.018	.011
	28	.053	.018
	90	.089	.028

Considère has stated that the shrinkage of cement in air may vary from 0.15 to 0.2 per cent. for neat cement, and from 0.03 to 0.05 per cent. for mortar poor in cement; and, similarly, he has found that pure cement swells under water from 0.1 to 0.2 per cent., and that concrete poor in cement swells from 0.02 to 0.05

upon these figures, since the apparatus used was crude and the number of tests was small.

Art. 13.—The Coefficient of Expansion Due to Temperature Changes.

The earliest work recorded concerning the linear thermic expansion of concrete is due to Bouniceau, who published his results in the "Annales des Ponts et Chaussées," 1863, page 178. His work was performed on rectangular prisms 65 to 94 inches long and about 7 inches on each side, the blocks being placed in water whose temperature varied from 10 to 95 degrees C. The apparatus used was checked by measuring the determined coefficient of expansion for other materials.

Bouniceau tested altogether ten blocks, either of solid stone, concrete, mortar or neat cement, the latter being in all cases Portland; the following are the results obtained on the cement mixtures:

Neat Portland cement................	.00000594 per degree F.
One cement to two silicious sand.......	.00000655 " " "
Concrete (proportions not given) (stone being silicious gravel)..............	.00000795 " " "

Professor W. D. Pence of Purdue University has made a series of investigations, the results of which are given in a paper of the Western Society of Engineers, November, 1901. He

made experiments on Portland cement concretes of the compositions shown in the following table. The values there given show the coefficient of linear expansion per degree Fahrenheit.

TABLE I.

Kind of Concrete	Coefficient of Expansion
1 Cement 2 Sand 4 Broken Stone	.0000055
1 Cement 2 Sand 4 Gravel	.0000054
1 Cement 5 Gravel	.0000053

The method of conducting these experiments involved the comparison of the concrete bars with metal bars, and the results obtained may perhaps be regarded with some suspicion on this account. Büsing and Schumann, in "Portland Cement," page 77, quote Meier as giving the coefficient of expansion of neat cement between —5 to +25 degrees C. as being the same as for iron. Similarly, Christophe, in "Le Beton Armé," page 706, quotes Bouniceau, Meier, Bauschinger, Adie and Durand-Claye in stating that the coefficient may vary from .00000667 to .00000805 per degree F., and that it is essentially constant even with varying percentages of mixture.

Berger and Guillerme, in "Ciment Armé," page 84, quote Durand-Claye as giving the coefficient of expansion but little different from .0000075 per degree F.

In the early part of 1902 tests were made by Messrs. J. G. Rae and R. E. Dougherty, graduating students in Civil Engineering at Columbia University, on one bar of 1:3:5 gravel Portland cement concrete and one 1:2 mortar bar, the bars being four inches by four inches in cross-section and about three feet long, with an age of about five and one-half years.

The results found are as follows:

Mixture	Coefficient of Expansion per Degree Fahrenheit
1:3:5	.00000655
1:2	.00000561

percentages of magnesium-sulphate and magnesium-chloride, in addition to the ordinary salt, sodium chloride. The magnesium-sulphate and magnesium-chloride react either on the hardened cement or on the hydrated lime which is present in the cement and form calcium-sulphate and calcium-chloride. The calcium-sulphate crystallizes and expands, and therefore disintegrates the mass, but the calcium-chloride is soluble and simply deposits inert magnesia.

Dr. Michaelis believes that this chemical action can be annulled by adding to the cement some pozzalana, which, in combination with lime, has of itself the property of hardening under water. The lime which is needed must separate from the cement, since pozzalana does not harden by itself. Candlot and others think, however, that the difficulty is more easily solved by making the cement mixture impermeable to the water, and that, in order to avoid disintegration, it is simply necessary to prevent the sea water from attacking the interior of the mass. They believe, then, that if the addition of pozzalana is of value, it is only so because it provides a denser mixture.

Le Chatelier has formulated a new opinion on this question and attributes the disintegration, in large manner, to the presence of alumina. In that case the sulphates in the water attack the aluminate of lime and form sulpho-aluminate of lime, which swells and expands. Under those conditions Le Chatelier considers it advantageous to have as little alumina as possible in the

cement, or to replace it as far as possible by iron oxides. No extended tests have as yet been applied to this theory.

A complete discussion concerning the first two opinions may be found in Vol. XXXVII. of the Transactions of the American Society of Civil Engineers, including also a final statement of the Association of German Portland Cement Manufacturers upon the proposition of Dr. Michaelis. In this particular instance it is declared that cement mixtures for use in sea water are not improved by the addition of pozzalana or trass.

R. Feret has presented a paper, in Vol. IV., 1901, of the "Annales des Ponts et Chaussées," concerning the effect of the addition of pozzalana to Portland cements which are to be used in sea water. In the paper are recorded tests made upon several specially manufactured cements, marked G, R, T and A, which were afterward used in actual construction work in harbors. The G cements consisted of equal weights of good Portland cement and of lightly burned gaize*; the R cements consisted of equal weights of good Portland cement and Roman pozzalana; the T cements, of equal weights of good Portland cement and trass, and the A cements were manufactured from pastes containing about 23 per cent. of clay. The results obtained from these cements were compared to Portland cements of various brands, manufactured from a paste containing about 21 per cent. of clay. Tests were made in the waters of the harbors of Boulogne, Calais, Havre, La Rochelle and Bordeaux. The longest tests extended over a period of three and one-half years; and although the results obtained were not in all respects harmonious, it was found that the mortars made of the specially prepared cements were, in general, stronger and showed less signs of disintegration than the mortars made from the ordinary Portland cements. This was found to hold true, however, only when the mixtures were deposited under water. When the mixtures were allowed to harden in air it was found that the specially prepared cements possessed little strength, even after an interval of two years. The ordinary cements naturally attained their usual strength. Feret

*Gaize—A light, porous stone of variable degree of hardness, resulting from the silification of certain clays.

although the question is being studied with great care by the Society of German Portland Cement Manufacturers, who estab-

TABLE I.

Mixture	Ratio in Percentages of Tensile Strength of Sea Water vs. Fresh Water Hardening				
	Age in Weeks				
	1	4	26	52	104
1 Cement, 1 Sand	92.0	93.7	93.3	89.6	92.6
1 Cement, 2 Sand	89.3	92.2	90.0	90.5	88.2
1 Cement, 4 Sand	92.6	92.7	77.5	78.6	80.5
1 Cement, 4 Sand, ¼ Hydrat Lime	99.4	88.8	87.1	74.3	87.7
1 Cement, 1 Sand, ½ Hydrat Lime	91.5	67.7	76.3	77.6	74.0

lished, in 1894, with the aid of the Prussian government, an experiment station on the island of Sylt, in the North Sea. It is there also that it is proposed to determine finally the soundness of the theory advanced by Dr. Michaelis concerning the admixture of pozzalana in concrete which is to remain in sea water.

Strength in Sea Water—The strength of cement mixtures does not increase as rapidly in salt water as in fresh. Experiments set forth by Dyckerhoff in the Proceedings of the Association of German Portland Cement Manufacturers, 1896, are shown in Table I., in which are given the ratios in percentages of tensile strengths of mortars hardening in salt and fresh water. The table shows some irregularities in regard to the mixtures including lime, the older mixtures of which, although furnishing high

resistance at the time of setting, also showed marked signs of disintegration.

Table II. furnishes very similar results, and is taken from Büsing and Schumann's "Portland Cements," page 128, from experiments made by Sympher on the crushing resistance of mortars when deposited in weak sea water. The relations between results of the fresh and sea water specimens is very satisfactory, although in the last case shown the specimens were attacked and partially destroyed in the sea water.

Table III. is taken from the Report of the Boston Transit Commission for the year ending June 30, 1902, and shows the effect of keeping briquettes in compressed air, in fresh water and

TABLE II.

Mixture	Hardening in	Ultimate Crushing Resistance in Lbs. per Sq. In. at the Age of			
		4 Weeks	52 Weeks	104 Weeks	Remarks
1 Cement, 1 Sand..	Fresh Water.	4230	6330	6880	
	Sea Water...	3440	4340	5420	
1 Cement, 2 Sand..	Fresh Water.	3640	5000	5300	
	Sea Water...	3530	4320	4590	
1 Cement, 3 Sand.. ¼ Hydrat Lime....	Fresh Water.	2840	3560	4190	
	Sea Water...	2340	3400	3820	
1 Cement, 4 Sand.. ½ Hydrat Lime....	Fresh Water.	2210	2640	2880	
	Sea Water...	2110	2340	2340	Edges broken off; disintegration in sea water

in sea water. The briquettes were of the usual type used in tensile testing, the mixture used being 1 part of cement, 2½ parts of fine crushed stone, ranging in size from an impalpable powder to ⅛ inch in diameter, and 4 parts of coarse crushed stone, ⅛ to ¼ inch in size. All the briquettes were kept in air at 60 to 80 degrees Fahr. for the first twenty-four hours after making, and then in compressed air at a pressure of 18 to 25 pounds per square inch for thirteen days; they were then divided into three lots and placed as shown in the table. Each figure is a mean of three briquettes. The results shown belong to Vulcanite cement only, but other brands acted similarly.

It will be seen that the briquettes kept in compressed air were always the strongest, and that up to the age of four months there was no practical difference between those kept in fresh water and

Sea Water (Under the Harbor)..........	420	533	543

experiments on the hardening of cement mortars in fresh and sea water. Table IV. is an abstract of these tests. Each result shown is a mean of six tensile briquettes of .775 square inch cross-section and of two compressive cubes whose area of cross-section was 7¾ square inches.

TABLE IV.

Age	Ultimate Resistance in Lbs. per Square Inch							
	Neat Cement	Mortars Composed of 1 Cement, 3 Standard Quartz Sand, by Weight	Mortars Composed of 1 Cement, 3 Fine Gravel by Weight, Mixed with Trowel to Plastic Consistency					
	Mixed With and Immersed in Sea Water		Mixed With and Immersed in Sea Water		Mixed With and Immersed in Fresh Water		Mixed With Fresh Water and Kept in Air	
	Tension	Tension	Tension	Compression	Tension	Compression	Tension	Compression
4 Weeks...	422	149	95	327	71	469	70	426
12 Weeks..	——	——	115	——	88	——	77	——
1 Year.....	736	275	179	540	146	731	173	838

It will be seen that the tension and compression tests do not furnish uniform results; the tension specimens hardening in sea water are stronger than those hardening in fresh water. This is not true of the compressive specimens, whose crushing resistance, moreover, is exceptionally low. The cement used in these

tests had the following fineness: 50 per cent. passed a sieve having 32,300 meshes per square inch; 31 per cent. passed a sieve of 5,800 meshes per square inch, but was retained by previous sieves, and the remaining cement was retained on the 5,800 mesh screen.

It may then be concluded that, unless mixtures fail by disintegration, their strength under sea water approximates that attained under normal conditions, but is never greater. And, finally, disintegration may be avoided, either by making the mixture impermeable or by adding some substance such as pozzalana.

Gauging with Salt Water—The action of ordinary salt solutions on the strength of cement mixtures still remains to be considered.

Figure 1 is taken from tests reported by A. Noble in Vol. XVI., 1887, of the Transactions of the American Society of Civil Engineers. The figure shows the effect on the tensile strength of one cement to one sand mortar briquettes when mixed with water containing various percentages of salt. It will be seen that there is but very little loss in strength when the water contains small percentages of salt, and not much more loss even when the percentages rise to 16.

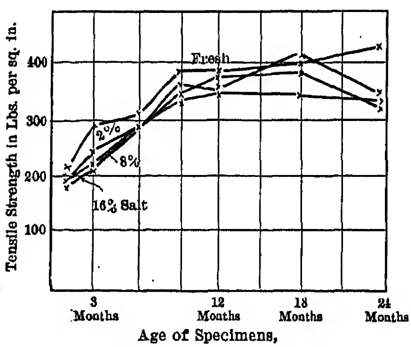


FIG. 1.—NOBLE'S TESTS.

E. C. Clarke records very similar experiments in Vol. XIV. of the same Transactions; in this case briquettes were gauged with fresh water and with salt water, and were also immersed in both fresh and salt water; the results show no great variations in strength. Clarke states that the time of setting is somewhat retarded; in this he is corroborated by Heath, page 83, of his Manual of Limes, Cements and Mortars.

C. S. Gowen records in a paper read before the American So-

nitely stated that gauging cement mixtures with salt water does not affect the ultimate strength injuriously.

TABLE V.

Age	1:2 Briquettes		1:3 Briquettes	
	Tensile Strength in Lbs. per Square Inch, Gauged with			
	Fresh Water	Salt Water	Fresh Water	Salt Water
7 Days.........	236	126	112	68
1 Month.......	289	231	183	131
3 Months......	414	294	268	215
6 Months......	549	424	335	266
9 Months......	554	452	351	301
12 Months......	572	576	458	413

Art. 15.—Porosity and Permeability.

Porosity and permeability are terms often confused in meaning when applied to cement mixtures; but they apply to entirely different properties. Porosity is a measure of the voids and gives no indication of the connection of these voids with one another. Permeability, on the other hand, implies paths from one void to another. The question of porosity is not of the greatest importance, except as giving indication of the denseness of a mixture and perhaps, indirectly, an indication of its ultimate strength.

Due to the fineness of grinding and to the uniformity of grain, it is to be expected that neat cements should be more porous than mixtures of sand and cement. This is perhaps the more evident when neat cement is compared to concrete, since in the latter possibly 50 per cent. of the mass consists of large pieces of dense stone. However, in the case of concrete, it is clear that paths between the voids are more likely to exist than

in the case of neat cement, and that, therefore, the concrete may be the more permeable.

R. Feret, in a very valuable paper* published in Vol. IV., 1892, of the "Annales des Ponts et Chaussées," discusses fully the porosity and permeability of various kinds of cement mortars, and shows that the actual solid contents of a mixture are clearly indicated by the amount of water absorbed. He states that a mixture in which the fine sands predominate is always the more porous; the permeability, however, varies inversely to the porosity.

Feret's experiments were carried on with three sizes of sand grains; a coarse sand, which would correspond to a sand passed by a No. 5 sieve and retained on a No. 12 sieve; a medium sand, which would correspond to a sand retained between a No. 12 and a No. 50 sieve, and a fine sand, all of which would pass a No. 50 sieve.

Feret's Conclusions—It is perhaps best to quote Feret's conclusions directly:†

(a) The permeability of a mortar depends less on the total volume of the voids than on their individual dimensions.

(b) The continuous passage of water through mortars diminishes the permeability very rapidly.

(c) The filtration of sea water through mortars often results in their more or less rapid disintegration.

(d) All other things being equal at the beginning of filtration, plastic mixtures are less permeable than dry; after some time this difference disappears, and it appears that, in the case of sea water, disintegration is not more rapid for one than for the other.

(e) In general mortars made with the same sand are the less permeable, as they contain the more cement.

(f) Mortars of the same richness, but of different granulometric sand composition, are disintegrated by the passage of sea water as rapidly as in proportion to the fine grains in the sand. The ef-

**Sur la Compacité des Mortiers Hydrauliques.*

†Page 143 of Feret's paper.

fects may not be the same for mortars which are simply placed in water.

A very full discussion on impervious concrete is also recorded in the Transactions of the American Society of Civil Engineers, December, 1903, and the work of various experimenters is cited. The general conclusion, there summarized by R. W. Lesley, is as follows: That neat cement mortars show the least permeability; that mortars with fine sand are less permeable than those mortars with coarse sand, and that the lessening of the permeability is due to the closing of the pores by lime, which is carried in suspension, in the process of filtration, through the mass, and which ultimately forms a coating on the surface of the masonry.

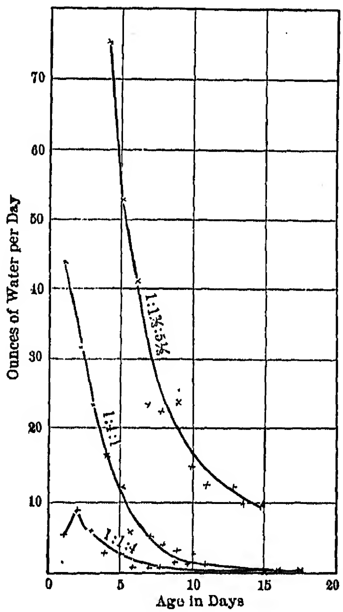


FIG. 1.

In almost all cement mixtures, even if permeability does exist in the beginning, it decreases very fast as the mixture ages, provided disintegration does not take place. This is very clearly shown by experiments reported in Vol. CVII., page 95, of the Proceedings of the Institution of Civil Engineers. Figure 1 is taken from that report and shows the filtration of sea water under a head of twenty-four feet, through one cubic foot of Portland cement concrete of the proportions indicated, three months old. It is seen how rapidly the amount of water which passes through the mass decreases with the time, even for widely varying proportioned mixtures.

Figures 2 and 3 are taken from Feret's paper, already noted. Figure 2 shows the initial permeability of two series of mortars, mixed with different proportions of sand and gauged with different percentages of water. The size of the specimens and the

surface through which the water passed are not given; the specimens set in air two weeks before being tested. The small initial permeability of the richer mixtures is immediately noted.

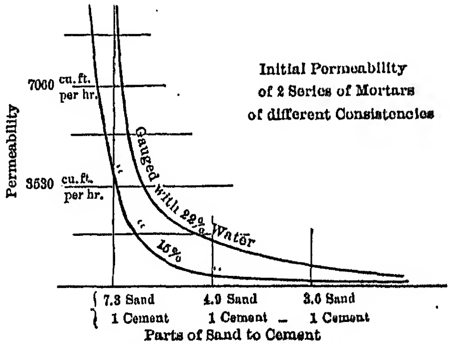


FIG. 2.—FERET'S TESTS.

Figure 3 shows the variation in the permeability of three mortars during the two first days of filtration; the experiments were continued for one year, and at the end of that time it was found that the percolation through the lean mixture had ceased, but

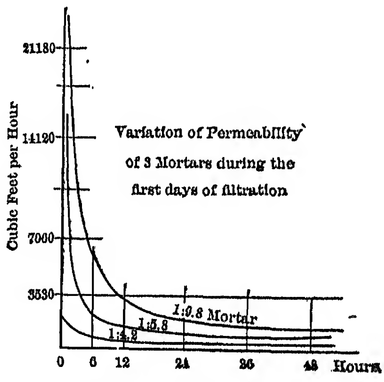


FIG. 3.—FERET'S TESTS.

that the other richer mixtures had been slightly attacked by sea water and were passing very small quantities of water.

Feret notes that the permeability decreases the more rapidly as the first filtration is the more abundant, and that the amount

passed is independent of the nature of the liquid (fresh or sea water).

In conclusion, inspection of existing concrete work is sufficient to show that almost any well balanced mixture can be made impervious to the passage of liquids; the greatest care in mixing, due to the non-homogeneity of the ingredients, must be observed. Where concrete masses do pass water, the permeability will in general be found to be due, not to some defect in the concrete itself, but to open cracks which may have been caused from one of various reasons, such as improper joining of work laid at different times, settlement of foundations or temperature changes.

The addition of salts or soaps to cement mixtures to cause impermeability has not been considered by the author; although many experiments have been made along such lines, the results are not in such form as to warrant the drawing of definite conclusions, the more so when it seems possible to make cement mixtures impervious without such aid.

Art. 16.—The Effect of Freezing on Cement Mixtures.

The effect of cold temperatures on the setting and hardening of cements has been much discussed, but appears at present to be very simple. It is now the opinion that the hardening properties of frozen cement are not impaired, if the freezing has taken place before the initial setting of the cement has begun. Under those conditions the physical action of the changing of the water into globules of ice has prevented the chemical action of the crystallizing of the cement particles; crystallization cannot take place until the ice globules return to the liquid form. No damage will then have been done, if freezing does not again take place before the cement has set; but if continued thawing and freezing take place, allowing an intermittent action of setting, it is very likely, under those conditions, that the cement will be injured. Many large pieces of concrete work have been built in freezing weather and have remained for long periods of time in a frozen condition, but, after thawing, have shown no evil effects. It is only necessary to bear in mind that the physical action of freezing must so far precede the beginning of the chemical action as to preclude the lat-

ter's taking place. The use of salt, glycerine or other substances in the water used for laying cements at cold temperatures seems, therefore, unnecessary, more particularly as there is always the possibility that these admixtures may prove injurious.

The percentage of injury done by the addition of salt substances may not be very great, and may often be nil, but it is probable that the use of these adulterants will cease.

Laboratory experiments made to determine the change in strength of mixtures gauged with salt water must be treated with some caution, since in the laboratory the experiments are made under normal temperature conditions, whereas in practice salt is added to cement mixtures only during freezing weather; the hardening of a cement under the latter condition may be very different.

It has already been shown in a preceding article that, in the case of laboratory experiments, there is but little, if any, decrease in the strength of the mixture, even when a 16 per cent. salt solution is used. Experiments made with salt mixtures during freezing weather have shown very similar results; but it seems unnecessary at the present time to record such experiments in any detail, since, as has already been stated, concrete mixed with fresh water is now laid at almost any temperature, and is found to suffer no ill effects, if alternate freezing and thawing do not take place. For such experiments with salt mixtures the reader is referred to tests made by E. S. Wheeler and recorded by him in the Report of the Chief of Engineers, U. S. Army, for 1895, page 2968 and following.

The following experiments, made at the Watertown, Mass., Arsenal on frozen cement mixtures, gauged with fresh water, are of exceeding value.

Table I. is taken from the Watertown Arsenal Report for 1901, and shows the crushing strength of two-inch cubes which were left for various intervals of time in a temperature of 0 degrees and were then exposed to a temperature of 70 degrees Fahr. It will be seen that the compressive strength did not vary to any considerable degree, no matter how long the specimen had been exposed to the freezing temperature, if it had been exposed

the same number of days at the 70 degree temperature. It is clear that no setting action takes place when the water in the mixture is frozen.

The results of tests on three brands of cements only is abstracted, since these are characteristic examples.

Tables II. and III. show the ultimate compressive resistance of two-inch cubes composed of neat Portland and natural cements and of 1:1 mortars subjected to low temperatures at the times of making. These experiments are also recorded in the Report of the Watertown Arsenal for 1901.

TABLE I.

Brand	Length of Time at 0° F.		Subsequent Length of Time at 70° F.	Compressive Strength in Lbs. per Sq. In.
	Months	Days	Days	
Star 1:1 Mortar ..... Portland Cement	——	5	7	846
	——	14	7	1000
	——	21	7	1010
	——	31	7	981
	2	——	7	981
	3	——	7	1010
Josson 1:1 Mortar... Portland Cement	——	7	7	1470
	——	14	7	1230
	——	21	7	1240
	——	29	7	1430
	3	——	7	1520
Hoffman 1:1 Mortar. Natural Cement	——	6	14	540
	——	15	14	527
	——	20	14	624
	——	28	14	561
	3	——	14	579

In Table II. there were three general groups of specimens; one was allowed to set in the open air of the testing laboratory at the ordinary atmospheric temperature, given in the report as 70 degrees Fahr. The specimens belonging to the other two groups were placed in a cold storage warehouse, where they remained different intervals of time. One group was placed in a room whose temperature was maintained at about 39 degrees, and the other group in a room whose temperature was in the vicinity of 0 degrees. Specimens intended for this last room were mixed on cold days, with the thermometer in the neighborhood of 15 to 20 degrees Fahr., and it was intended to freeze the

material as soon as practicable after mixing and use mixtures as wet as ordinarily employed in construction. The table shows clearly the lengths of time the various specimens were left under these varying temperature conditions and the length of time at which the frozen specimens were allowed to thaw under normal conditions. Careful examination will show that the frozen speci-

TABLE II.

Brand	Compressive Strength in Lbs. per Square Inch		
	Specimens Set in Air at 0° F., and Then Placed in Air at 70° F.	Specimens Only in Air at 70° F.	Specimens in Air at 39° F., and Then Placed in Air at 70° F.
	3 Mos. and 30 Days	30 Days	
Star Portland	3620	4570	———
Alsen Portland	2520	3900	———
	1 Mo. and 30 Days	30 Days	
Star Portland	3460	4570	———
Star 1:1 Mortar	1400	1960	———
Storm King Portland	1680	2520	———
	3 Mos. and 14 Days	14 Days	
Star 1:1 Mortar	1310	1970	———
Alsen Portland	2450	3780	———
Josson Portland	648	1160	———
Bonneville Natural	1020	800	———
Hoffman Natural	579	808	———
Norton Natural	832	744	———
		3 Mos. and 14 Days	3 Mos. and 14 Days
Star	———	4410	4280
		4 Months	3 Mos. and 1 Month
Storm King	———	2380	2700
Alsen	———	3510	6400
		3 Months	3 Mos. and 8 Days
Josson	———	3110	4970
		3 Mos. and 15 Days	3 Mos. and 15 Days
Austin	———	580	1480
		3 Months	3 Mos. and 13 Days
Bonneville	———	1720	2060
		4 Months	3 Mos. and 14 Days
Norton	———	950	1440

mens exhibited practically no deterioration in strength, if the time allowed them under normal temperature conditions was equal to that of the specimens of the same mixture to which they could be compared.

The specimens noted in Table III. were treated a little differently; the frozen specimens were kept frozen for various inter-

vals of time up to one year and then allowed to set for one day only under normal temperature conditions. It will be seen that the strength of the frozen material increased to some extent, showing some faint chemical action; but in no case did a frozen specimen one year old attain, even approximately, the strength of a normal specimen one month old.

C. S. Gowen presented a paper before the American Society of Testing Materials, July 3, 1903, in which are also recorded some tests on Portland cement mortar exposed to various cold temperatures. The tests were made on the standard form of

TABLE III.

Brand	Compressive Strength in Lbs. per Square Inch				
	Specimens Set in Air at Temperature 0° F. (One Day in Air at 70° F. Before Testing)			Specimens Set in Air at 70° F.	
	1 Month	3 Months	1 Year	1 Month	3 Months
Star Portland	1350	1720	2724	4350	4400
Star 1:1 Mortar	383	497	864	——	——
Storm King Portland	749	703	1370	2520	2430
Alsen Portland	986	1210	1580	3900	4040
Josson Portland	347	624	802	3970	3110
Austin Natural	238	241	333	724	661
Bonneville Natural	411	478	——	1140	1720
Hoffman Natural	206	276	428	1140	1070
Norton Natural	341	347	680	1000	1090
Obelisk Natural	225	274	358	1560	1240
Average	534	637	1015	2256	2085

tensile briquettes, composed of one part Giant Portland cement and two parts of crushed quartz sand. Table IV. shows the results obtained under normal temperature conditions; Table V., results obtained under freezing temperature. In the latter table each figure is an average of eight tests. It should be noted that the results recorded for the six months freezing temperature are subject to an error, due to the fact that the briquettes were continually in air up to that time and were probably dried out. The briquettes of nine and twelve months, made under the same conditions, were placed in water at the end of six months, and showed uniform increase in strength over the strength of one and three months.

TABLE IV.

Tensile Strength of 1:2 Mortar Briquettes

Age	Number of Specimens Broken	Average Tensile Strength in Lbs. per Sq. In.
28 Days	690	441
3 Months	215	563
6 Months	185	657
9 Months	155	671
12 Months	165	663

TABLE V.

Tensile Strength of 1:2 Mortar Briquettes

Series	Tensile Strength in Lbs. per Square Inch at Age of				
	28 Days	3 Months	6 M nths	9 Months	12 Months
A	370	474	366	553	553
B	458	455	347	381	586
C	371	413	314	452	510
D	272	360	287	567	602
E	255	246	300	437	512

Series A. Placed in cold air, 24-32 deg. F., immediately after mixing; fresh water used.

Series B. Placed in cold air, 24-10 deg. F., immediately after mixing; fresh water used.

Series C. Placed in cold air, 24-32 deg. F., after taking heavy Gillmore needle; fresh water used.

Series D. Placed in cold air, 20-10 deg. F., immediately after mixing; brine* used.

Series E. Placed in cold air, 20-10 deg. F., immediately after mixing; fresh water used.

J. S. Costigan records in the Transactions of the Canadian Society of Civil Engineers, 1903, some interesting tests on the effects of freezing neat cements, in which various briquettes were moulded under a pressure of twenty pounds per square inch. When these briquettes were twenty-four hours old they were all placed in water and allowed to remain there until they were seven days old, with the exception of some twenty-four hours during this period, when they were exposed to the action of

About 10% by weight, solution.

Table I. shows the adhesion of iron rods in concrete, as found by E. Mörsch and reported by him in "Beton und Eisen," Part III., 1903. It will be seen that the adhesion varies not only with the richness of the cement mixtures, but also with the percentage of water used in gauging.

TABLE I.

Percentage of Water	Adhesion in Lbs. per Square Inch							
	Richness of Mixture							
	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8
10 Per Cent.........	213	270	270	370	427	384	237	171
15 Per Cent.........	655	696	569	540	299	270	213	142
20 Per Cent.........	398	398	356	356	171	171	156	100
25 Per Cent.........	313	427	328	342	114	170	128	100

The table exhibits no positive fact, although, in general, the richer mixture furnishes the greater adhesion. Neither too little nor too much water is to be used in the mixing, since some intermediate percentage furnishes the greatest adhesion.

Professor Charles Spofford made a series of tests upon the holding power of different types of rods, which are reported in the same number of the publication. The concrete used was a Portland cement concrete of 1:3:6, the stone used being a mixture of two parts of one-inch trap and one part of one-half-inch trap. The concrete was wet sufficiently so that when tamped into the moulds water flushed to the surface. The rods were all thoroughly cleaned by a sand blast before the concrete specimens were made. Several types of rods were used—the Ran-

some rod, which is a square rod, but twisted through an angle of 20 degrees; the Thacher rod and the Johnson rod (the two latter

TABLE II.

Type of Rod	Cross Section of Rod in Inches	Mean Area of Cross Section of Rod in Sq. Inches	Cross Section of Concrete Block in Inches	Length of Rod Imbedded in Inches	Greatest Adhesion in Lbs. per Sq. In.	Remarks
Ransome.......	½ x ½	0.25	6 x 6	12	454	Concrete Split Longitudinally or Was Crushed on End in All These Cases; Sometimes Concurrently with Slipping of Rod.
"	"	"	"	16	228	
"	"	"	"	26	291	
"	"	"	8 x 8	12	310	
"	"	"	"	16	396	
"	"	"	"	26	260	
"	¾ x ¾	0.56	"	20	388	
"	"	"	"	24	399	
"	"	"	"	36	305	
"	1⅛ x 1⅛	1.27	10 x 10	27	245	
"	"	"	"	37	141	
"	"	"	"	50	138	
Thacher.......	½ x ½	0.18	6 x 6	12	222	
"	"	"	"	16	282	
"	"	"	"	26	223	
"	¾ x ¾	0.39	8 x 8	20	402	
"	"	"	"	24	290	
"	"	"	"	36	250	
"	1⅛ x 1⅛	1.03	10 x 10	27	238	
"	"	"	"	37	304	
"	"	"	"	50	268	
Johnson.......	½ x ½	0.19	6 x 6	12	508	
"	"	"	"	16	410	
"	"	"	"	26	264	
"	¾ x ¾	0.37	8 x 8	20	461	
"	"	"	"	24	347	
"	"	"	"	36	259	
"	1¼ x 1¼	1.17	10 x 10	27	313	
"	"	"	"	37	252	
"	"	"	"	50	242	
Plain..........	¾ round	0.44	8 x 8	24	271	Rod Slipped.
"	"	"	"	31	255	
"	"	"	"	36	219	
"	¾ x ¾	0.56	"	24	274	
"	"	"	"	31	243	
"	"	"	"	36	221	
"	1⅛ x ½	"	"	24	159	
"	"	"	"	31	201	
"	"	"	"	36	185	
"	1½ x ⅜	"	"	24	226	
"	"	"	"	31	188	
"	"	"	"	36	164	
"	2¼ x ¼	"	"	24	42	
"	"	"	"	31	165	
"	"	"	"	36	145	

being well known forms of specially rolled rods), and also plain round, square and flat rods. All tests were made twenty-eight days after mixing of the concrete.

Table II. shows the value of the adhesion in pounds per square inch obtained by these different bars. Of the various plain forms, it will be seen that the round bars show the greatest adhesion and the flat bars the least. In general the adhesion decreased as the depth to which the rods were imbedded was increased, but no conclusive superiority of one kind of bar as compared to another can be shown; moreover, in many cases the rods did not pull out at failure, but the blocks were split. The true adhesion was not found in those cases.

Table III. shows the values of adhesion of round iron rods, determined by Professor W. K. Hatt and reported by him before the American Section, International Association for Testing Materials, at its annual meeting of 1902. The table gives averages of three tests each, the concrete being a mixture of 1:2:4 and its age about thirty-two days.

TABLE III.

Size of Rod	Depth of Rod in Concrete in Inches	Ultimate Adhesion in Lbs. per Sq. In. of Rod Surface
7-16 Inch...........	6.0	636
5-8 Inch............	6.4	756

E. S. Wheeler records, on page 2940 of the Report of the Chief of Engineers, U. S. Army, for 1895, a considerable number of tests made upon the adhesion of iron bars in cement mixtures. In the first set of experiments, shown in Table IV., the mixture was composed of one part, by weight, of Portland cement to two parts of sand, the latter being limestone screenings passing $\frac{3}{8}$-inch slits; the age of the mortar was one month. The bars were imbedded to depths varying from 8 to 10 inches; they were in the form of bolts, being cut from bar iron, and were without fox wedges. The twisted bolts were formed by twisting a piece of one-inch square bar iron, the length of the twisted portion being 8 inches. The periphery of a twisted bolt was taken to be the circumference of a circle whose diameter was the distance be-

tween opposite corners of the bolt after twisting; a core of mortar of this diameter was torn from the bar in pulling. It is seen that the increase in resistance of the twisted to the plain bar is not very great.

The tests shown in Table V. differ only in that ordinary river sand was used, the mixtures used being neat, 1:2 and 1:4. The bolts were imbedded 2 to 10 inches.

TABLE IV.

Description of Bolt	Mortar	Number of Bars Tested	Average Adhesion in Lbs. per Sq. Inch
Plain, ½ In. Diameter, Round.....	1 Cement, 2 Sand	3	447
Plain, 1 In. Diameter, Round......	" "	3	556
Plain, 1¼ In. Diameter, Round....	" "	3	524
Plain, ½ In. Square..............	" "	3	543
Plain, 1 In. Square..............	" "	4	562
Plain, 1¼ In. Square............	" "	3	434
1 In. Sq., Twisted 1 Turn in 8 Ins..	" "	3	608
1 In. Sq., Twisted 2 Turns in 8 Ins.	" "	3	516
1 In. Sq., Twisted 3 Turns in 8 Ins.	" "	3	561

In the Watertown Arsenal Report for 1901 are reported various tests made on the adhesive resistance of $\frac{1}{2}$x$\frac{1}{2}$ inch steel bars imbedded in Portland cement concrete prisms 6x6x18 inches long. The age of the prisms was about thirty days and their average crushing resistance about 2,278 pounds per square inch. It was found that the adhesion of the rods per square inch aver-

TABLE V.

Mortar	No. of Bars Tested	Average Adhesion in Lbs. per Sq. In.
Neat Cement................	5	313
1 Cement, 2 Sand............	15	264
1 Cement, 4 Sand............	10	111

All bolts were plain, 1 inch in diameter, and round.

aged 204 pounds per square inch of surface, with a maximum value of 296 pounds and a minimum of 77 pounds per square inch. Three other prisms, whose crushing resistance was 4,210 pounds per square inch, gave an average adhesion of 297 pounds per square inch. The rods were imbedded various lengths from 2 to 12 inches.

Considère has made some experiments upon the adhesion of iron rods in concrete in a different way from other experimenters; and since his values are calculated upon an assumed condition of internal stress, too much weight should not be placed on these results. His values for iron wire of .17 inch diameter, whose surface was perfectly clean, shining, and possibly somewhat greasy, were found to vary from 70 to 170 pounds per square inch of surface, for concrete kept in the air. The resistance to sliding increased to 256 pounds for prisms of the same concrete, reinforced by larger rolled iron rods .24 inch in diameter, and in other experiments, in which the surface of the .17 inch diameter iron wires was slightly rusted, the sliding resistance varied from 330 to 500 pounds per square inch. In these last tests the specimens were kept under water. He found

TABLE VI.

Diameter of Wire in Inches	Condition of Wire Surface	Resistance per Sq. In. of Surface at Cessation of Adherence in Lbs.	Resistance per Sq. In. of Wire Rod at Cessation of Adherence in Lbs.
0.14	Smooth	502	33500
"	Barbed, with Split Ends	493	33100
0.12	Smooth	442	35200
"	Barbed, with Split Ends	423	34000
0.10	Smooth	286	27400
"	Barbed, with Split Ends	356	34100

that the resistance to sliding bore some relation to the amount of water used; for instance, in three prisms made alike and in which the first had an excess of water, the second was normal concrete and the third was too dry, the resistances were respectively 155, 170 and 70 pounds per square inch.

De Joly records in Vol. III., 1898, of "Annales des Ponts et Chaussées," some very interesting experiments which he made on the adhesion of anchor rods fastened by means of neat Portland cement in holes drilled in granite blocks. Three sizes of round iron rods were used—.14, .12 and .10 inches in diameter. The depth of the holes in the granite blocks was 23.6 inches. The cement was allowed to harden one month in air. De Joly comes to this very interesting conclusion: That the ultimate ad-

:sive resistance does not depend on the surface of contact be- een the two materials, but on the elastic limit of the inserted n rod.

Table VI., which is characteristic of several series of experi- ents, shows how the adhesive resistance per square inch of ntact surface varies at the cessation of adherence between the two materials from 286 to 502 pounds per square inch; but if the adhesive resistance is expressed in pounds per square inch of the rod cross-section the values so obtained show no very great variation for the different sizes of rods.

Experiments are recorded by De Joly for various qualities of iron rods and show very uniform results, according to this method of reasoning, which is correct, when the length of bar imbedded is so great that the ultimate resistance developed by the adhesion is greater than the resistance of the imbedded bar at its elastic limit.

In conclusion, it seems proper to take the ultimate adhesive resistance of iron rods in concrete as between 250 and 400 pounds per square inch of surface.

Art. 18.—The Fatigue of Cement Mixtures.

The question of the fatigue of cement mixtures has lately received some discussion, although the matter is probably not of the very greatest importance. Professor J. L. Van Ornum h presented in the Transactions of the American Society of Ci Engineers, December, 1903, a paper in which he records com- pressive tests made upon neat Portland cement cubes two inches on the side, which were crushed when four weeks old. The ultimate strength was determined in the usual way with one continuous application of the load, and, in addition, similar blocks were subjected to repeated loadings of certain percentages of the ultimate strength, varying from 95 to 55 per cent. of the same. In the latter case the load was applied and removed repeatedly until failure occurred. Figure 1 shows the results obtained from ninety-two tested blocks.

The same subject has also been considered by De Joly, who has recorded the results of his experiments in "Annales des

are shown in Table II. In this case the rapidity of the applications varied from 92 to 26 per minute, and it will be seen how

TABLE II.

Age of Specimens in Days	Ultimate Tensile Resistance in Lbs. per Sq. In., with One Application of Load	Number of Applications of a Load, Intensity of 200 Lbs. per Square Inch Before Rupture — Rate of Application: 92 per Minute	52 per Minute	26 per Minute
4	271	0	2	75
5	328	7	34	398
6	361	36	174	More than 2300
7	364	16	173	None less than 3000

very rapidly the number of applications increased as the time between applications increased. Table I. seems to indicate that there might be a limit of fatigue to a material, so that a load, if

TABLE III.

Brand of Cement	Age of Briquette	Number of Applications of Tensile Load of 200 Lbs. per Sq. In.	Ult. Resistance in Lbs. per Sq. In. — After One Application of Load: Tension	Compression	After Treatment as in Column 3: Tension	Compression	Remarks
Demarle .	12 days	5000	558	4800	507	4900	No rest after repeated loading.
Demarle .	14 "	"	525	5380	521	5070	Tested 24 hrs after repeated loading.
Demarle .	7 "	6500	421	3600	400	3620	1½ hrs' rest after repeated loading.
Demarle .	15 "	20000	560	6400	545	6170	No rest after repeated loading.
Demarle .	20 "	"	573	6900	523	6950	48 hrs' rest after repeated loading.
Demarle .	1½ years	"	857	14800	834	13450	48 hrs' rest after repeated loading.
Candlot. .	7 days	40000	552	5350	490	5420	No rest after repeated loading.
Candlot. .	11 "	"	576	7300	545	7100	Av'ge 12 hrs' rest after repeated load'g
Sollier. . .	4½ months	"	681	9470	618	9860	No rest after repeated loading.
Sollier. . .	5 "	"	708	10200	666	10300	48 hrs' rest after repeated loading
Demarle .	1½ years	"	848	14400	826	14100	48 hrs' rest after repeated loading.

applied sufficiently, although below the rupture point, might finally cause failure. Table II. shows, however, that, given sufficient time between applications, the material may not sustain any injury.

Table III. is also abstracted from De Joly's paper; it shows the ultimate tensile and crushing resistance of a cement of various ages, first, when subjected to only one application of the final load, and also, of similar specimens, after the elapse of various periods of time after having been subjected to repeated applications of a tensile stress of 200 pounds per square inch. Each result shown is an average of three tests, the specimens used being the French type of tensile briquette.

It will be seen in this case that, although the final tensile resistance is slightly lowered, no appreciable change occurs in the compression pieces.

It will require many experiments of a character similar to these quoted to determine definitely whether there is in concrete, as there is in steel, a critical point above which the material should never be stressed if it is never to fail at loads below the usual ultimate resistance.

CHAPTER IV.

ELASTIC PROPERTIES IN GENERAL.

Art. 19.—Treatment of Stress-Strain Curve.

The deformation that appears in a material which is subjected to any form of stress determines, in connection with the stress, its elastic properties. A diagram which shows the stress-strain relations throughout the entire range of stress is, therefore, of great assistance in showing clearly the elastic properties of any material.

In direct tension and compression tests this diagram consists of a curve which shows the relative elongation or shortening of the specimen for each intensity of stress; in flexure tests the curve illustrates the ratio between deflections and the loads applied, and in torsion tests the ratio between the twist and the applied moment. In this treatise, however, torsion stresses will not be considered.

The stress-strain curve for tension and compression specimens needs no explanation, but it will be well to consider its algebraic equivalent. The general designation of this relation is the coefficient or modulus of elasticity. It is usually denoted by E and expresses the ratio for any stress between the unit stress p and the unit strain l; that is,

$$E=\frac{p}{l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

This ratio E does not possess a constant value for any material between a point of no stress and the ultimate; that is, the ratio is never represented by a straight line between the origin of co-ordinates and the point representing the breaking load. The curve is, indeed, very complex for the majority of materials used in construction; but it is a straight line from the zero stress to a

point called the elastic limit, the latter point being, in fact, that point where E changes in value.

In the case of some materials it has been found that every stress, however small, causes a permanent strain or set to remain in the specimen after the removal of the stress. This involves slightly the proper method of calculating E. It may be determined by dividing the unit stress either by the total unit strain in the specimen or by the elastic unit strain, which is the total unit strain less the unit set. In the opinion of the author, the proper method to employ is the second, which determines what will be called hereafter the "elastic" coefficient of elasticity.

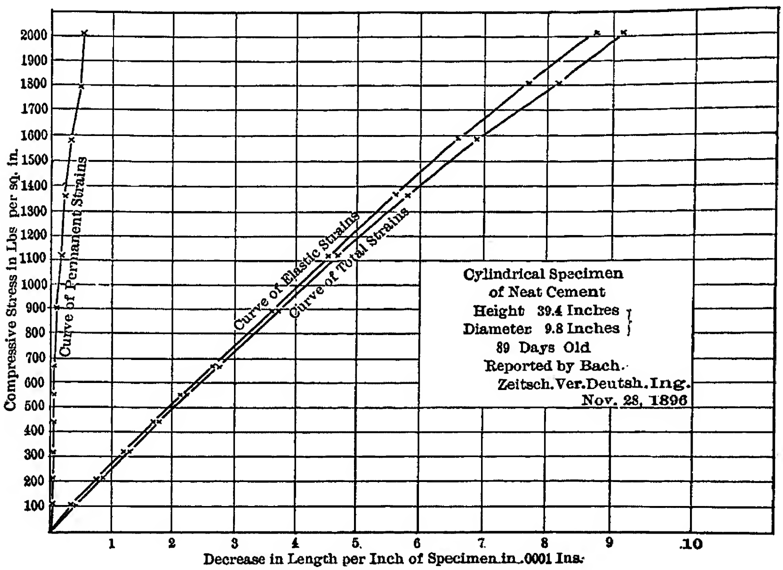


FIG. 1.

This method is illustrated by Figure 1, which is taken from a test on a round cylindrical specimen of neat cement 39.4 inches high, 9.8 inches in diameter and 89 days old, reported by Professor C. Bach in the "Zeitschrift des Vereines Deutscher Ingenieure," February 28, 1896. Three curves are shown, the curve marked elastic strain being obtained by subtracting from the curve of total strain the curve of sets. The curve of sets, it

should be noted, is obtained by determining for the load indicated in the figure, the strain remaining in the material after the load is entirely removed. This curve of elastic strain may be expressed by an algebraic equation, which Professor Bach thinks may take the following form:

$$E=\frac{p^n}{l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

in which E represents the coefficient of elasticity; p, the unit stress applied to the specimen; l, the corresponding elastic strain, and n, a numerical exponent. As already explained, in the case of a majority of materials used in engineering work, this curve of elastic strain is a straight line up to the elastic limit. For that portion of the curve the coefficient n becomes equal to 1 and the coefficient of elasticity is a constant quantity.

To find the tangent of the inclination $\frac{dp}{dl}$ of this stress-strain curve at any point, it is only necessary to differentiate the equation $E=\frac{p^n}{l}$. There will then be obtained

$$\frac{dp}{dl}=\frac{E}{np^{n-1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

When p equals 0, and when n is greater than 1, Eq. 3 shows that $\frac{dp}{dl}=\infty$, and the tangent becomes vertical at the origin of coordinates. If n is less than 1, and for $p=0$, $\frac{dp}{dl}=0$, and the tangent is horizontal at the same point. If n equals 1, then $\frac{dp}{dl}=E$ and the coefficient is a constant quantity.

Another method of calculating E determines what might be called the instantaneous value of the coefficient of elasticity, and is obtained by finding the elastic strain occurring between any two applied loads and assuming that the curve is a straight line between two such points. This involves no particular error if the points chosen are sufficiently near together.

Again, the value of the coefficient of elasticity has been de-

K and M constants. By taking the first differential of this equation there is obtained

$$\frac{dp}{dl}=E=K-2Ml$$

that is, E, or the ratio of stress to strain, is equal to a constant quantity, less the product of a different constant, by the unit deformation at the point considered. If M equals zero, the curve becomes a straight line and the value of the coefficient constant.

One other point remains to be considered before discussing in detail the results of any experiments, and has reference to the number of times a single load should be applied before proceeding to the next higher load. Professor Bach, for instance, repeats his loading between the initial load and the load in question until he obtains always the same value of the strain. This involves, in most cases, removing a load five times, and sometimes still more. Other experimenters apply a load usually but once, and, after having obtained the corresponding strain, proceed either to the next higher load or first determine the set for the load in question. It appears possible, by the frequent repetition of loads, to change the molecular structure of the material so that it fails to furnish the results which are desired. This applies particularly to loads above the elastic limit for materials possessing such limit. As far as practice is concerned, however, in determining the behavior of materials in construction, Profes-

sor Bach's method seems to be the proper procedure, since in that case there is a constant repetition of the application of the loads; in practice, however, the element of time which appears between the applications of loads is sufficiently great to allow the material time to recover completely. This is not the case in laboratory work, where the times of application of the loads can never be at very great intervals, although even there, as has been shown,* it requires but very little time for a cement mixture to be restored to its original condition.

Since much use will be made of the reports of the Watertown Arsenal, it will be well to state at this point that the values of the coefficient of elasticity in the Watertown Arsenal reports were obtained, in all cases, by dividing the difference between the initial and some greater load by the difference between the total and permanent deformations for the loads in question. In that treatment the coefficient was then assumed to be a straight line between the initial load and the point of loading considered. Unless the coefficient is actually a constant quantity throughout the entire range of loading, every change of loading will furnish a different value. These coefficients cannot very well be called either the instantaneous or the elastic coefficients; but since they probably do not differ greatly in value from either, they will in this treatise be directly compared to the true coefficients.

Inspection of a stress-strain curve will determine at once the quantities which express in numerical figures the values of the usual elastic properties, viz., the coefficient of elasticity, the elastic limit and the ultimate resistance.

**See Art. 18 on Fatigue of Cement Mixtures.*

A valuable paper on the tensile coefficient of elasticity of Portland cement mixtures is recorded by De Joly in Vol. III., 1898, of the "Annales des Ponts et Chaussées." His tensile tests were conducted on two sizes of bars, the first 41 inches long by 1x1.5 inches in section, and the other 47 inches long by 4.7x6.5 inches in section. Both sizes of specimens had enlarged heads in the manner of the ordinary tensile briquette. The elongations, in all cases, were measured on a gauged length of 39 inches. Various specimens were made with different brands of Portland cements. Both sizes of specimens were made from neat cement, but con-

TABLE I.—SPECIMENS OF NEAT CEMENT.

No. of Specimen	Age in Days	Coefficient of Elasticity in Lbs. per Sq. In.	Determined for a Tensile Stress of Lbs. per Sq. In.	Ultimate Tensile Resistance in Lbs. per Sq. In.
1.........	28	2,680,000	187	——
2.........	40	3,160,000	342	483
2.........	40	3,070,000	448	
3.........	50	3,550,000	142	476
3.........	50	3,380,000	256	
3.........	50	3,190,000	398	
3.........	50	3,130,000	455	
4.........	106	4,500,000	271	617
4.........	106	4,270,000	542	

crete mortar specimens were made only in the large size. The small specimens were kept in fresh water until the times of testing, which varied; but the large specimens were always kept in damp air until broken; this was always thirty days after making.

Table I. shows the results obtained with the smaller sized bars and Table II. some results on the larger ones.

De Joly states that no definite point could be termed the elastic limit, but that it seemed to be very near the point of rupture for the neat cement specimens, and that it never fell below three-fourths of the ultimate resistance in the case of mortars or concretes. De Joly states that this does not seem to apply to compression tests on cement mortars, since some other experiments made in the Laboratory de l'École des Ponts et Chaussées show that the elastic limit is well defined for compression and its value is little greater than one-half the ultimate resistance. The coefficients of elasticity as marked in these tables are the true or elastic coefficients.

Examination of these tables shows that the coefficient of elasticity is greater for mortars and concretes than for neat mixtures, at least in the case of specimens one month old and kept in moist air. The coefficients increase with age in the case of neat cements, but do not change materially with the sizes of the specimens. In another table, not quoted, De Joly shows that the value of the coefficient does not change sensibly for different brands of cements; he also states that the value of the coefficient for tension for any one neat, mortar or concrete specimen is constant, and, as compared to the coefficient of elasticity for compression, is equal, or greater, but never less.

TABLE II.

Composition of Specimens Approximately in Parts by Weight			Cross Section of Specimen in Sq. Ins.	Average Value of Coefficient of Elasticity in Lbs. per Sq. In.	Average Ultimate Tensile Resistance in Lbs. per Sq. In.
Cement	Sand	Stone			
Neat	——	——	31	2,560,000	338
I	2.4	——	31	3,000,000	141
I	1.5	1.5	31	3,040,000	135

The following series of tensile tests on reinforced concrete prisms is also recorded by De Joly in the same volume of the "Annales des Ponts et Chaussées" and is of exceeding interest. Figure I shows the character of the specimens with which the tests were made. The specimens of Type No. I, which were both neat, mortar and concrete mixtures, contained three bars of round iron .78 inch in diameter, placed as shown; all other types were neat cement only. Type No. II. contained five bars

of iron of the same dimensions, placed as shown. Type No. III. contained either one round bar .78 inch in diameter, placed at the centre and continuing throughout the entire length of the concrete, or two bars, as shown under the figure marked Type III. In Type No. IV. six specimens were prepared, each of which contained two bars, also of the same diameter, placed sym-

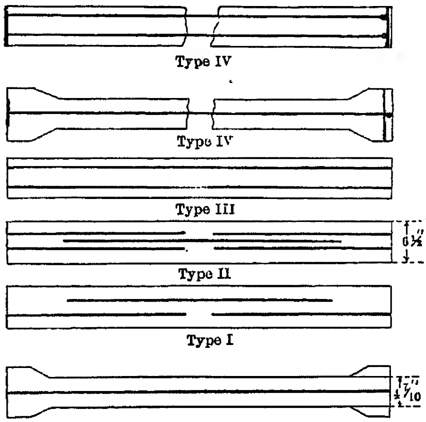


FIG. 1.

metrically in the beam and continuing throughout the entire length; but in four of these specimens the rods were fastened solidly at the ends by means of flat plates. De Joly states that it was impossible to determine any elastic limit from the stress-strain curves; it appeared to be near the point of rupture. This means that the apparent coefficient of elasticity is practically a constant quantity; it is calculated by dividing the unit stress on the bar, obtained by dividing the total load by the total cross-section, by the unit deformation of the bar.

The addition of metallic reinforcement increases the value of the coefficient of elasticity of a cement mixture, but this increase is never more than 50 per cent.; at least Table III. shows this to be so for specimens of Type No. III.

In none of the experiments was De Joly able to determine exactly the ultimate resistance of the reinforced specimens. Various reasons are given for this, and it is therefore better to omit these values.

The results given in Table III. are each an average of one to three specimens; in the case of the specimens of Type No. III., the spacing apart of the two bars is increased from the first to the fourth tests, there shown, so that in the fourth test the bars are very near the surface of the specimen. It will be seen, then, that the coefficient of elasticity increases as these same bars vary their position within the specimens, from the centre to the outside. The great difficulty of making tensile tests on reinforced concrete specimens is clearly shown by the last statement, which shows the unequal distribution of stress through the cross section; reasoning would tend to show that the exterior of specimens of the kind shown carries the greatest part of the stress. Reasoning further, it seems, then, that iron imbedded in the very centre of concrete specimens will influence the stress-strain diagram of the

TABLE III.

Specimen of Type No.	Reinforced or Not	When Stress on Cross Section is Lbs.	Coefficient of Elasticity in Lbs. per Sq. In.		
			Neat Cement	Mortar	Concrete
I.	No	——	2,550,000	3,000,000	3,030,000
I.	Yes	——	3,740,000	3,960,000	4,260,000
III.	No	6160	2,560,000	——	——
III. (with 1 bar)	Yes	"	2,720,000	——	——
III. (with 2 bars)	"	"	3,540,000	——	——
III. (with 2 bars)	"	"	3,670,000	——	——
III. (with 2 bars)	"	"	3,820,000	——	——
III. (with 2 bars)	"	"	3,900,000	——	——

Minimum cross section of all specimens about 30 square inches.

combined material but little, and inspection of Table III. confirms this reasoning. It appears, therefore, that but little knowledge can be gained of the elastic behavior of these two materials in combination by making direct tensile tests of the kind indicated.

And these results are confirmed by experiments made by the author and recorded in succeeding pages.

W. H. Henby has recorded in the Proceedings of the Association of Engineering Societies for September, 1900, a very interesting set of experiments on the elastic properties and ultimate strength of stone and cinder concretes under both tensile and compressive stresses. These tests were made at Washington University as thesis work. The tension specimens, made in

Num		Cem	San	Ston	Cement	Size Stone		Weig per C	Sq. In.	Ultin Lbs.		
8	7	1	2	4	L	1½	Air dry	—	2,000,000	130	Dry	
16	30	1	2	4	"	1½	"	142	2,882,000	198	"	
17	30	1	2	4	"	1½	"	148	4,727,000	227	"	Very dense spec.
295	64	1	2	4	A	2	Air	151	7,744,000	252	"	
315	30	1	2	4	"	2	"	149	8,360,000	183	"	Failed in shoulder.
316	30	1	2	4	"	2	"	148½	7,280,000	214	"	
22	60	1	2	5	"	1½	Air dry	144	1,857,000	111	Very dry	
25	60	1	2	5	"	1½	"	146	3,253,000	128	Dry	
26	60	1	2	5	"	1½	"	146	3,023,000	189	"	
30	90	1	2	5	M	1½	"	140	3,776,000	142	"	
106	90	1	2	5	A	1½	"	144	3,696,000	129	Very dry	
107	90	1	2	5	"	1½	"	144	3,896,000	93	"	
287	63	1	2	5	"	2	Air	146	4,980,000	154	Dry	
288	63	1	2	5	"	2	"	146	3,744,000	192	"	
96	30	1	3	6	"	2	"	150	3,810,000	119	"	
271	30	1	4	8	"	1½	Water	149	6,108,000	125	"	
23	90	1	3	—	M	—	Air dry	136	3,988,000	199	"	Failed in shoulder.
24	90	1	3	—	"	—	"	139	5,202,000	234	"	
117	120	1	3	—	"	—	"	136	5,144,000	144	Very dry	
118	120	1	3	—	"	—	"	136	5,150,000	154	"	
18	30	1	2	4	L	1½	"	142	2,269,000	191	Plastic	
35	55	1	2	4	"	1½	"	147	4,543,000	149	"	
65	96	1	2	4	"	1½	"	146	3,992,000	190	"	
66	96	1	2	4	"	1½	Air	147	4,760,000	226	"	
72	8	1	2	4	A	1½	"	157	3,720,000	213	"	
67	100	1	2	4	L	1½	Air dry	147	5,075,000	209	"	
18	30	1	2	4	A	2	Air	148	3,306,000	192	"	
222	30	1	2	4	"	1½	"	153	3,750,000	223	"	
223	30	1	2	4	"	1½	"	150	3,600,000	241	"	
224	30	1	2	4	"	1½	Water	158	3,550,000	279	"	
283	65	1	2	4	"	2	Air	144	3,810,000	143	"	Failed in head.
284	65	1	2	4	"	2	"	149	3,724,000	102	"	
286	65	1	2	4	"	2	Water	150	5,440,000	82	"	
3	14	1	2	5	M	1½	Air dry	139	2,000,000	85	"	Not well ram'd.
5	18	1	2	5	"	1½	"	—	2,106,000	120	"	
78	7	1	2	5	A	1½	Air	152	3,968,000	147	"	
236	30	1	2	5	"	1½	"	145	4,532,000	165	"	Failed in head.
237	30	1	2	5	"	1½	"	152	4,425,000	242	"	
241	30	1	2	5	"	1½	Water	155	5,000,000	239	"	
91	7	1	3	6	"	1½	"	154	3,828,000	115	"	
242	30	1	3	6	"	1½	Air	147	———	130	"	
243	30	1	3	6	"	1½	"	147	2,427,000	104	"	
244	30	1	3	6	"	1½	"	148	2,440,000	128	"	
245	30	1	3	6	"	1½	"	144	4,496,000	93	"	
270	30	1	4	8	"	1½	"	143	3,553,000	71	"	
235	95	1	—	—	M	—	Water	137	6,423,000	645	"	Failed in head.
10	18	1	2	4	"	1½	Air dry	—	2,286,000	75	Excess	
36	90	1	2	4	"	1½	"	147	3,500,000	125	"	
165	120	1	2	4	"	1½	"	143	3,473,000	136	"	
166	120	1	2	4	"	1½	"	144	3,473,000	89	"	

A indicates Atlas Brand Cement; M indicates Medusa Brand; L indicates Lehigh Brand.

TABLE IV.—*Continued.*

TENSILE TESTS OF CINDER CONCRETE.

Number of Test	Age in Days	Composition Parts of: Cement	Sand	Stone	Brand of Cement	Size of Broken Stone in Inches	Treatment	Weight in Lbs. per Cubic Foot	Modulus of Elasticity Lbs. Per Sq. In.	Ultimate Stress Lbs. per Sq. In.	Net Ult. Compress. Resistance Lbs. per Sq. In.	Remarks
43	7	1	2	4	A	—	Air	118	1,854,000	46	—	—
44	7	1	2	4	"	—	"	114	1,892,000	—	—	—
46	7	1	2	4	"	—	Water	122	1,826,000	—	—	—
141	30	1	2	4	"	—	Air	113	2,800,000	133	993	—
149	30	1	2	4	"	—	Water	121	2,909,000	77	1,415	—
159	30	1	2	5	"	—	Air	109	2,853,000	86	1,039	—
155	30	1	2	5	"	—	"	107	2,329,000	86	1,054	—
167	30	1	2	5	"	—	"	102	1,820,000	78	688	—
171	30	1	2	5	"	—	Water	126	1,900,000	76	1,166	—
174	30	1	2	5	"	—	Air	112	1,900,000	129	1,005	—
132	60	1	2	5	"	—	Air dry	117	2,413,000	97	882	—
2	12	1	2	5	M	—	"	113	1,428,000	60	—	—
195	60	1	3	6	A	—	"	110	1,274,000	58	699	—
198	60	1	3	6	"	—	"	110	1,892,000	88	949	—
202	60	1	3	6	"	—	"	107	2,215,000	62	677	—
207	60	1	3	6	"	—	"	108	2,922,000	52	—	—
186	30	1	3	6	"	—	Water	114	1,422,000	41	653	—
209	30	1	3½	7	"	—	Air	102	1,034,000	30	409	—
212	30	1	3½	7	"	—	"	104	937,000	31	510	—

A indicates Atlas Brand Cement; *M* indicates Medusa Brand; L indicates Lehigh Brand.

length of 11 inches. The deformations were determined for both kinds of stress by means of a dial extensometer having friction rollers and measuring by means of a vernier needle to .0001 of an inch. The tensile elongations were measured on a gauged length of 10 inches, the compressive deformation on a length of 6 inches. Three brands of Portland cement were used—Atlas, Lehigh and Medusa. The sand used was Mississippi River sand and the stone was 1½ to 2 inch limestone macadam, taken in the same condition in which it came on the market. The total volume of voids in the 2-inch macadam was 57¾ per cent.; in the 1½-inch macadam, 61¾. The cinders used were unscreened. All the measurements were volumetric. It was found that the average density of the stone concrete compression specimens was greater than the average density of the tensile specimens.

Table IV. shows the ultimate tensile resistance and the modulus of elasticity of both stone and cinder concrete specimens; they are tabulated in the order of their consisten
being the dry specimens, then the plastic, then the excess. From the figures accompanying the original report it may be presumed that the coefficients as calculated are not the true elastic coeffi-

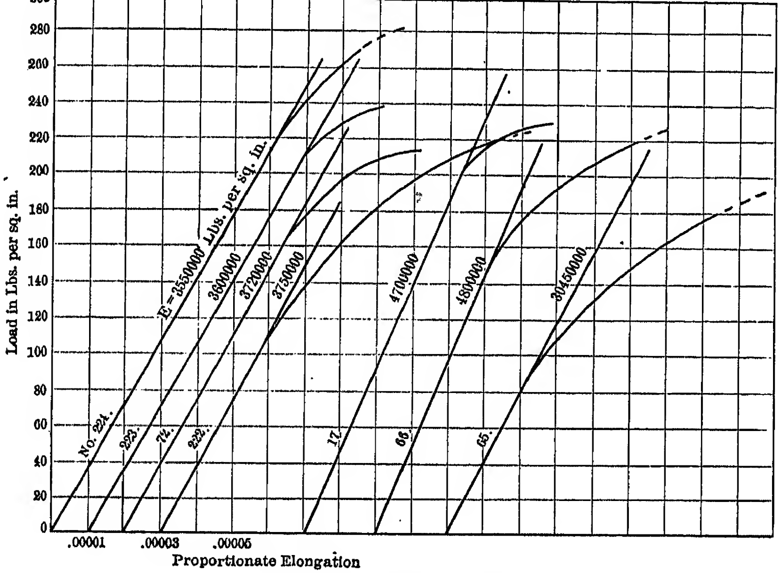


FIG. 2.—HENBY'S TESTS.

laboratory or in water, as marked. Henby concludes that the greatest strength is developed in the case of the dry mixtures in which ramming is required to flush water to the surface. In that case the density and the ultimate strength increase together. The air dry specimens show lower results than the air specimens, and the concretes which set in water attained greater strength than either of the others. This does not appear to be the case, however, for the cinder concretes. The results show that the coefficient of elasticity increases slightly with the age of

the specimen, and perhaps slightly with the denseness of the mixture. This is equivalent to saying that the coefficient increases with the ultimate resistance.

Table IV. also gives tensile results found with cinder concretes. It will be seen that the ultimate tensile resistances are very low, averaging perhaps 75 pounds per square inch. The coefficients of elasticity are also lower than in the case of the stone concrete specimens and they decrease with the leanness of the mixtures.

Figure 2 is taken from Mr. Henby's paper and shows the characteristic stress-strain curves for seven tension tests of 1:2:4 stone concretes. An elastic limit might be placed at about two-thirds of the ultimate resistance.

In some other tensile experiments, not here tabulated, Henby found that some cinder concrete specimens thirty-three days old, one part Atlas cement, three sand and six cinder, gave an average value of the coefficient for dry specimens of 2,368,000, and for wet specimens of 898,000 lbs. per sq. in. It will be seen that the dry specimens are much more resistent to deformation than the wet.

Henby also made the following experiments on eight cinder concrete specimens of the tensile form. All the specimens were first set in damp cloths for forty-eight hours and were then kept in dry air for twenty-eight days. Half of the batch were then put in water for three days. The average tensile resistance of the four dry specimens was found to be 89 pounds per square inch, and of the four wet specimens, 46 pounds per square inch. One half of the halves of the dry tensile specimens were then mmediately tested to failure by compression; the other half were ested after being in water forty-eight hours. Also, half of the ialves of the wet specimens were tested immediately and the other half were dried at 125 degrees Fahr. for forty-eight hours before being broken. The four specimens which had never been n water averaged 827 pounds per square inch; the eight wet specimens, 734 pounds per square inch, and the four dry specinens broken after having been dried averaged 1,008 pounds per square inch.

It will be seen, then, that these specimens when tested wet de-

The size of the specimens was 4x4 inches square, and the elonga-
ions were measured on a length of $17\frac{1}{2}$ inches, although the specimens were about 30 inches long. The values of the ulti-
nate strength as given are not very satisfactory, as many of the
bars broke in the head; but Professor Hatt believes that the
strength of the body of the bars was not different from the loads
recorded at the point of rupture of the heads. The mixture was

TABLE VI.

Number of Bar	Composition	Age in Days	Compressive Coefficient of Elasticity in Lbs. per Sq. In.	Determined At a Compressive Stress of Lbs. per Sq. In.	Ultimate Crushing Strength in Lbs. per Sq. In.
1	1:2:4 Stone...	9	4,702,000	750	2880
1	1:2:4 Stone...	9	3,940,000	1500	2880
2	1:2:4 Stone...	14	4,340,000	750	2575
2	1:2:4 Stone...	14	3,680,000	1500	2575
3	1;2:4 Cinder..	9	558,600	——	495
4	1:2:4 Cinder..	9	553,000	——	595
5	1:2:4 Cinder..	7	630,000	——	416
6	1:5 Gravel....	6	2,088,000	——	1185

composed of 1 part Peninsular Portland cement and 2 parts of clean, sharp pit sand, of which 84 per cent. was retained on a No. 30 sieve, and 4 parts of broken limestone, all of which passed through a one-inch sieve and of which 75 per cent. was retained on a $\frac{1}{4}$-inch sieve.

The coefficient of elasticity was computed with regard to the

set experienced after previous loads; in other words, it is the "elastic" modulus of elasticity.

Table VI. furnishes values of the compressive coefficient of elasticity for concrete cylinders 12 inches high and 8 inches in diameter, also reported by Professor Hatt in the same paper.

In addition to the concrete mixture noted above, tests were made on a 1:2:4 cinder concrete and a 1:5 gravel concrete, the gravel being a good quality of coarse gravel. The intensity of stress at which the compressive coefficient of elasticity was computed is shown in the table.

These experiments show the coefficient for compression to be considerably larger than for tension, but Professor Hatt has lately (Western Society of Engineers, 1904,) published the results of a greater number of tests, and he states definitely that he finds no appreciable difference between the two moduli. Table VII., taken from the latter paper, is otherwise self-explanatory;

TABLE VII.

Kind of Concrete.—Parts of				Age in Days	Coefficient of Elasticity in Lbs. per Sq. In.		Ultimate Strength in Lbs. per Sq. In.	
Cement	Sand	Broken Stone	Gravel		Compression	Tension	Compression	Tension
1	2	5	——	90	4,610,000	5,460,000	2413	359
1	2	5	——	28	3,350,000	3,800,000	2290	237
1	——	——	5	90	4,800,000	4,510,000	2804	290
1	——	——	5	28	4,130,000	4,320,000	2405	253

the results being averages of thirty-seven compression and twenty-seven tension specimens; the broken stone was limestone, being the product of the crusher below 1 inch, and the gravel excellent pit gravel, including sand and pebbles. The concrete was mixed medium wet.

The following tests on the tensile strength and the tensile coefficient of elasticity of concrete were made in the Mechanical Laboratory of the Department of Civil Engineering of Columbia University under the author's supervision by Walter T. Derleth and John Hawkesworth, graduating students of the fourth class in civil engineering. The work was begun early in 1903 and lasted until the first part of June, 1904. The cement which was

inch at the end of 7 days and 671 pounds per square inch at the end of 28 days. Mortar briquettes, one cement to three normal sand, gauged with about 8 per cent. of water, averaged 148 pounds per square inch at the end of 7 days and 203 pounds per square inch at the end of 28 days.

The sand which was used in making the concrete was Cow Bay, and was clean and sharp. Its fineness, as tested by standard sieves, was as follows:

Retained	by	No.	2	sieve	0.49%
"	"	"	3	"	1.15%
"	"	"	4	"	6.68%
"	"	"	20	"	9.52%
"	"	"	30	"	15.55%
"	"	"	50	"	38.90%
Passed	"	"	50	"	27.7%

The percentage of voids in the sand was determined to be 40.5 per cent. The stone which was used for the concrete was a blue limestone, broken into sharp, angular pieces, varying in dimensions from 3 inches to ½ inch. The percentage of voids, determined by an average of two tests, was 48.1 per cent. All the concrete for the tests was composed of one part of cement to three parts of sand and five parts of broken stone, by volume; and these ratios by volume correspond very closely to the actual weights of the different constituents used in the mixture. Each specimen or bar contained about 1¼ cubic feet of concrete, and each was prepared separately from a batch of the materials

which averaged about 1½ cubic feet. The sand and cement were first thoroughly mixed dry and then the moistened broken stone was added, the whole being turned several times before the addition of water. Water was then slowly added while the material was being turned over by shovels until its consistency was very plastic. The concrete was then deposited in the wooden moulds and lightly rammed into place with a wooden rod. After the first five bars had been moulded, it was found better to make the mixture so fluid that very little tamping was necessary; its consistency was then what is known as "very wet concrete."

The moulds were always well moistened, and also greased with soft soap, before depositing the concrete, and no trouble was experienced in removing the bars from the moulds. The pins were covered with paraffined paper, so that they were easily withdrawn after the specimen had set. It was found impracticable to remove the specimens from the moulds before four or five days. Specimens Nos. 2, 3 and 4 broke during the manufacture, due to improper handling or too early removal from the moulds. In order to strengthen the heads of the specimens in the neighborhood of the pins through which the tensile pressure was later applied looped pieces of iron telegraph wire or heavy-weight picture wire were inserted.

The shape of the specimens is clearly shown in the following figure, the cross section of each piece being 6x6 inches and the diameter of the pin hole through the head being 1¾ inches.

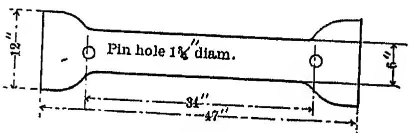
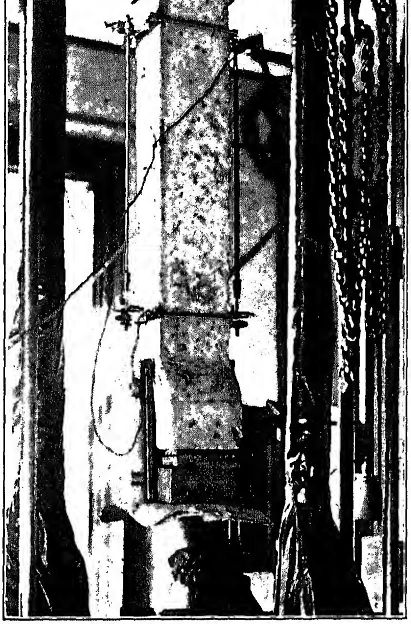


FIG. 3.

For the purpose of measuring the stretch or decrease in length of these specimens, upon the application of loads, it was necessary to have built a special extensometer. This piece of apparatus was made by T. Olsen & Co. of Philadelphia, and consisted of two frames which inclosed the specimen and which were firmly fastened to it at a distance apart of 25 inches; on opposite



ing Method of Determining the Elastic Behavior of Concrete Bars, 6x6-Inches in Cross-Section, the pecimens, with Electric Extensometer Attached, being Mounted for Tension Experiments in the 50,000 Pound Emery Testing Machine of Columbia University. In the Photographs, as Shown, e Test-Pieces Are Blocked Up with Wooden Wedges. The First Specimens Tested Were Hung om Heavy Steel Cables, with Looped Eyes, but a Second, and Better Method of Attachment, by eans of Parallel Side Plates, is Shown in the Right-Hand Figure. Enlarged Views of the Heads of e Specimens Are Shown Opposite Page 120.

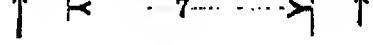


FIG. 4.

the micrometer head was divided into 250 parts, so that each division of the head represented .0001 of an inch. It was found impracticable to measure smaller parts than one division of the head. The accuracy of the screws was tested by means of a dividing engine in the laboratory of the Physics Department of Columbia University, and was found to be exact for the range of testing for which the instrument was designed.

Tests were also made upon concrete bars of the same form which were reinforced by wrought-iron bars, and it will be convenient to record at this point the results of tests made upon these wrought-iron bars.

Three bars were tested—one $\frac{3}{4}$ of an inch square, which developed an ultimate resistance of 48,700 pounds per square inch, with a coefficient of elasticity of 29,620,000; one bar $\frac{1}{2}$ inch square showed an ultimate resistance of 54,800 pounds per square inch and a coefficient of elasticity of 29,900,000, and one bar $\frac{5}{8}$ of an inch square had an ultimate resistance of 52,275 pounds per square inch and a coefficient of elasticity of 27,590,000.

Failure of the specimens, in the tensile tests, occurred in all cases but two, in the head, on each side of the pin hole. The wires imbedded in the head were not broken, but had slipped

in the concrete. The ultimate tensile resistances are therefore not of any value; the stress conditions at the pins in members of this shape are so peculiar that in future it will be well to devise some other method of applying the stress than the one which was used. In the compression tests none of the specimens was

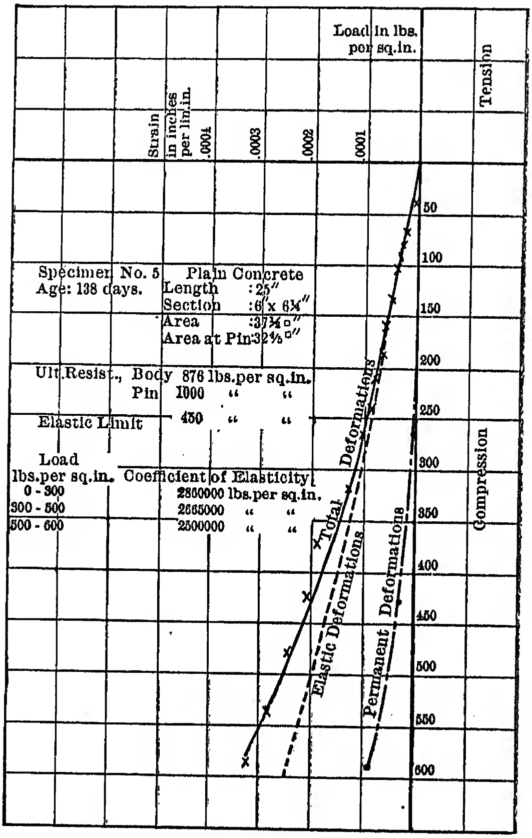


FIG. 5.

stressed to such an extent as to cause failure in the body of the bar; failure occurred generally by crushing or shearing at the heads or at the pin holes, but was usually accompanied by fine cracks appearing generally over the entire surface, so that the

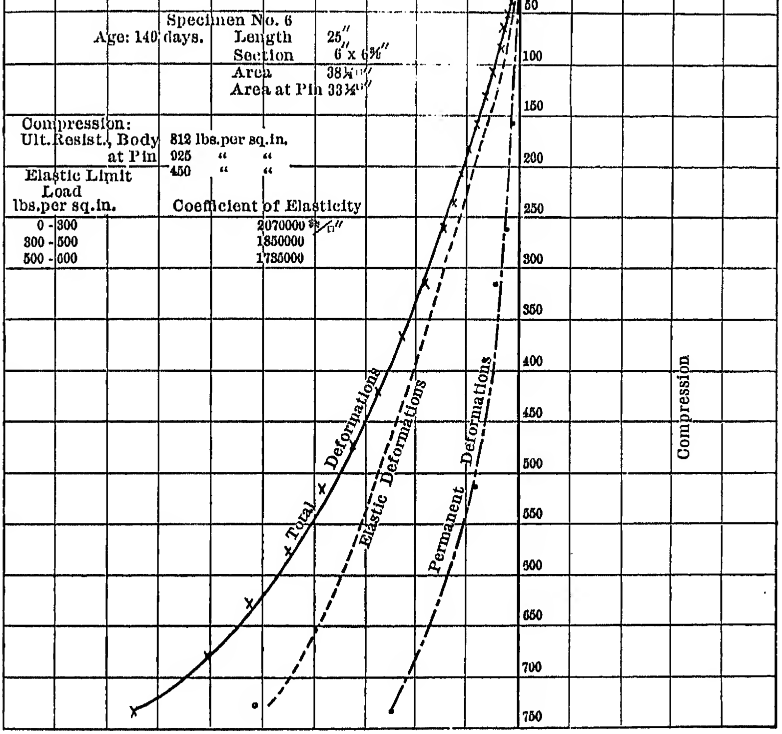


FIG. 6.

ultimate resistance was very nearly developed. None of these considerations concerning methods of failure disturbs, however, the measurements of the elastic deformations. It should be

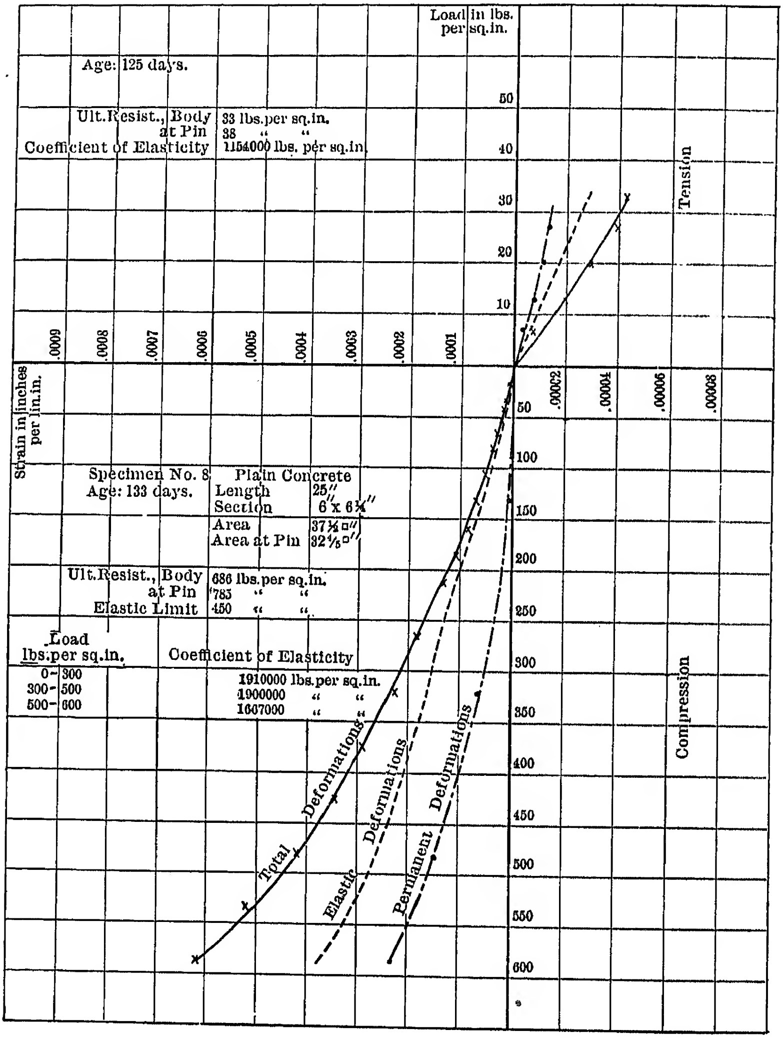


FIG. 7.

noted, however, that both kinds of stress, tension and compression, were applied, in the order named, to every individual specimen. This was done in order to eliminate from the results any

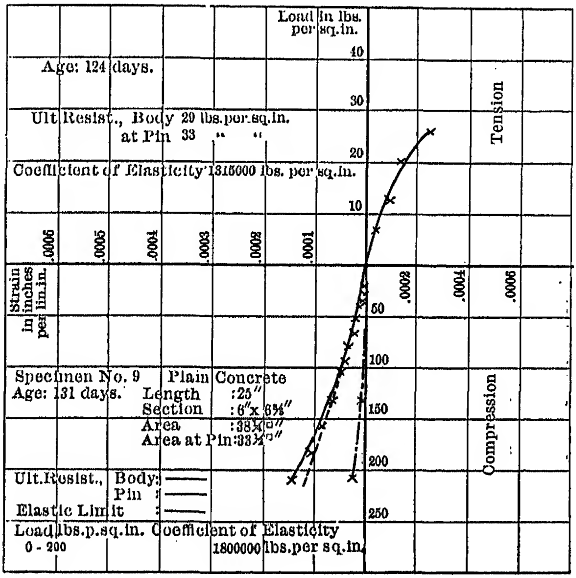


FIG. 8.

and to shearing tests. The manner of loading in the latter case is shown in Figure 4, page 87.

It is the opinion of the author that the size of broken stone used in these tests was too large. In bars 6x6 inches in section 3 inch stone is too large; it would have been preferable if 2 inch stone had been the limiting size.

The stress-strain curves for specimens Nos. 5, 6, 8, 9, 11, 22

and 23 are shown in Figures 5 to 11 respectively; it will be seen that the curves for tension and compression are very nearly straight lines, with equal inclinations.

Table IX., page 96, shows the results of tests made in the Laboratory of the Technical Institute of Vienna during 1891 and 1892, and are recorded in the Transactions of the Austrian Society of Civil Engineers for 1895.

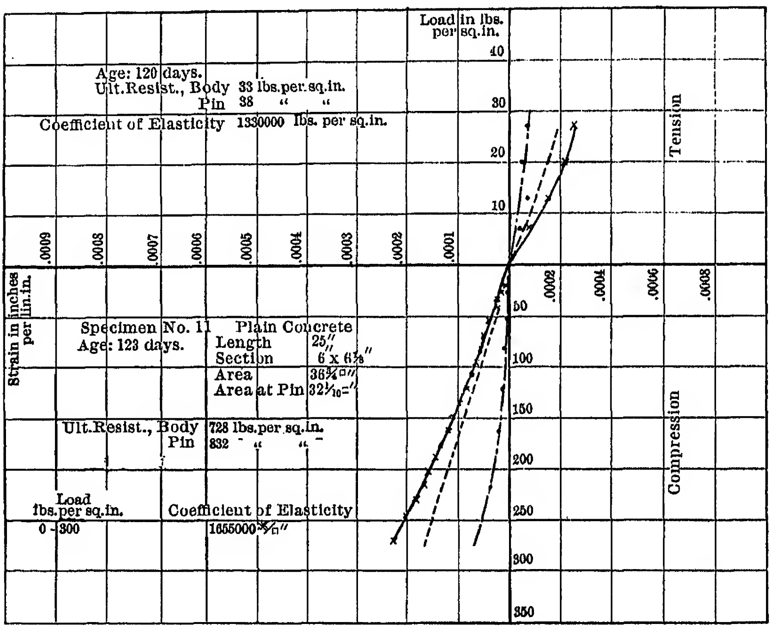


FIG. 9.

The batch numbers marked Wa were left in water three months from the day of making, being removed three days before the test; batch numbers marked Wb were left in water the entire time.

The table gives the ultimate compressive resistance of 4 inch cubes and of $3\frac{1}{2}$x$3\frac{1}{2}$x10 inch prisms. The strains experienced by the latter were also measured, so that it was possible to obtain

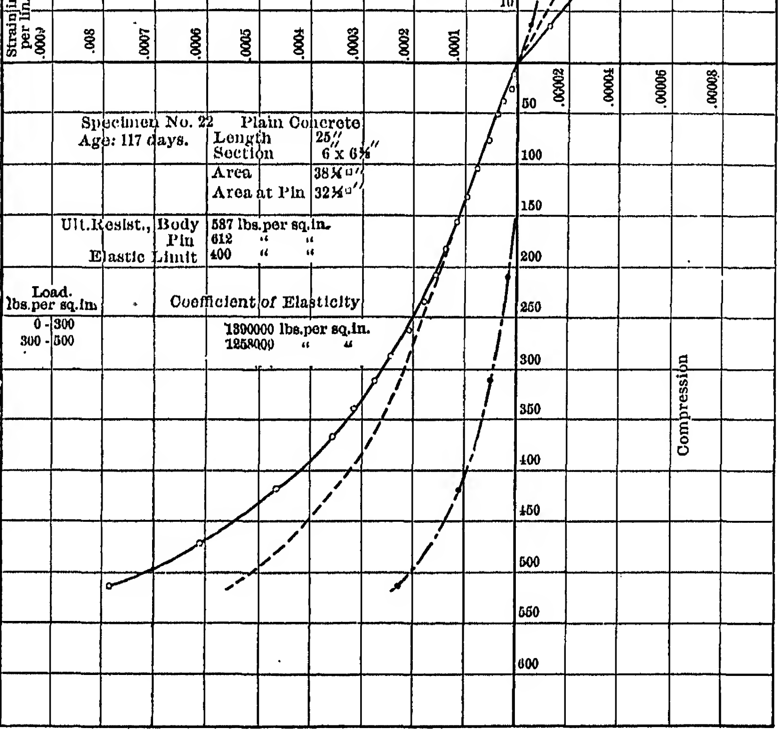


FIG. 10.

of the ultimate resistance and the coefficient of elasticity of concrete and mortar specimens in tension. It was found that the concrete prisms had permanent sets at relatively low stresses.

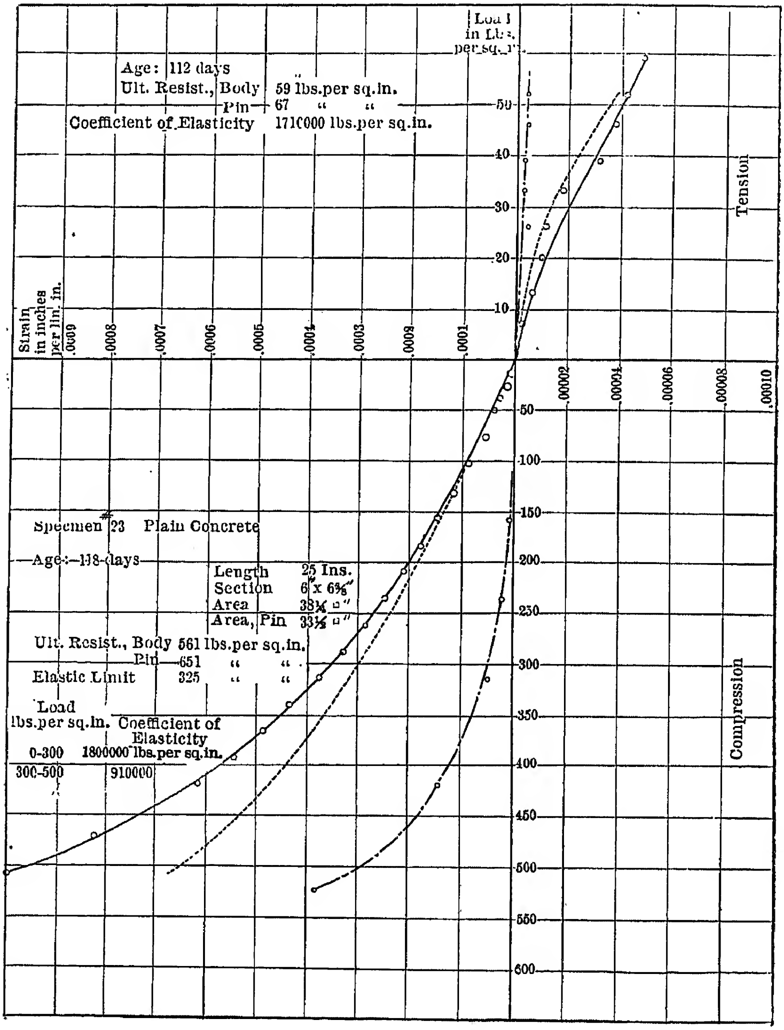


FIG. 11.

The report states that the total strain in both tension and compression was nearly always proportional to the loadings, but that this cannot be set down as a rule. Nor could the tests decide

TABLE VIII.

TENSION		COMPRESSION					Ult. Crushing Resistance		Ult. Shearing Resist.	
Ultimate Resistance in Lbs. per Sq. In. at Pin Section	Coefficient of Elasticity in Lbs. per Sq. In.	Age in Days	Ultimate Resistance in Lbs. per Sq. In. at Pin Section	Coefficient of Elasticity in Lbs. per Sq. In. Between Intensities of Stress in Lbs. per Sq. In. 0 to 300	300-500	500-600	Of 6 Inch Cube in Lbs. per Sq. Inch	At Age of Days	In Lbs. per Sq. In.	At Age of Days
56	2,315,000	—	—	—	—	—	1870	177	195	169
—	—	138	1000	2,860,000	2,665,000	2,500,000	—	—	314	165
42	1,250,000	140	925	2,070,000	1,850,000	1,735,000	1246	164	166	164
38	1,154,000	133	785	1,910,000	1,900,000	1,667,000	1196	157	187	157
33	1,315,000	131	—	1,800,000	—	—	—	—	—	—
—	—	—	—	—	—	—	863	151	158	151
38	1,330,000	123	832	1,655,000	—	—	—	—	—	—
31	781,200	—	—	—	—	—	—	—	—	—
49	880,000	117	612	1,390,000	1,258,000	—	922	128	104	128
67	1,710,000	118	651	1,080,000	910,000	—	600	128	65	128
Of the Composite Section at Centre of Bar	Of Composite Section		Of the Composite Section at Centre of Bar	Of Composite Section						
41	183,000	—	—	—	—	—	—	—	—	—
45	178,900	131	526	878,000	889,000	896,000	—	—	—	—
56	1,086,000	129	737	931,000	1,170,000	1,190,000	—	—	—	—
59	834,000	119	—	991,000	991,000	—	—	—	—	—
51	1,000,000	129	533	1,111,000	1,111,000	1,111,000	—	—	—	—
55	1,120,000	125	631	1,156,000	1,350,000	1,350,000	—	—	—	—
57	1,140,000	126	497	1,410,000	1,324,000	1,224,000	—	—	—	—
—	1,000,000	—	—	—	—	—	—	—	—	—
47	1,350,000	134	466	1,331,000	1,290,000	—	—	—	—	—
—	1,050,000	—	—	—	—	—	—	—	—	—

of stone was reduced to pea size.
-section at the centre of the bar was taken in calculating the coefficient of elasticity.

TABLE IX.

Mixture	Batch No.	Compression: 4 Inch Cubes: Number of Specimens	Age in Months	Average Ult. Resistance in Lbs. per Sq. In.	Specific Gravity	Compression: 3½ x 3½ x 10 Inch Prisms: Number of Specimens	Age in Months	Average Ult. Resistance in Lbs. per Sq. In.	Average Coefficient of Elasticity Lbs. per Sq. In.	Tension: Number of Specimens	Age in Months	Average Ult. Resistance in Lbs. per Sq. In.	Average Coefficient of Elasticity Lbs. per Sq. In.
1 Cement, 3 Danube Sand	I.	3	4	3698	2.24	3	4	3058	5,476,000	3	11	347	5,106,000
	II.	1	4	2105	2.26	3	4	2034	3,371,000	3	11	314	3,499,000
	III.	3	4	2958	2.28	3	4	2731	4,736,000	3	11	310	4,466,000
1 Cement, 3 Sand, 5 Shingle	I.	2	3	1529	2.17	1	3	683	1,054,000	2	6	129	1,394,000
	I. Wa	1	3	2432	2.23	1	3	1835	——	1	6	188	2,830,000
1 Cement, 2 Sand, 3 Shingle	I.	2	3	3641	2.10	2	3	3755	——	2	6	354	3,982,000
	I. Wa	1	3	3698	2.33	1	—	3570	4,367,000	1	6½	321	——
1 Cement, 1 Sand, 1 Shingle	I.	2	3	2162	2.22	2	3	2859	3,755,000*	2	6½	257	3,556,000
	I. Wa	1	3	3911	2.24	1	3	3428	4,736,000	1	6½	424	5,078,000
1 Cement, 3 Sand (unwashed)	I.	4	1½	3385	2.31	4	3	2845	5,177,000†	4	5	243	5,689,000
	I. Wb	3	3	3627	2.31	3	3	3172	4,665,000†	3	5	255	6,215,000

*One specimen only. †Average of 2 specimens.

From the foregoing experiments it is possible to draw the following conclusions:

First. Concrete in tension appears to possess no point which might be termed the elastic limit; in other words, the coefficient of elasticity is a constant quantity from a condition of no stress to the point of rupture.

Second. The coefficient of elasticity appears to increase with the ultimate tensile strength of the material, but, due to the great difficulty in determining the actual breaking loads of concrete bars in tension, it seems impossible to connect in any rational manner the coefficients with the breaking loads.

Third. The ultimate tensile resistance varies in some manner with the richness of the mixture and with the age of the specimen, but it appears impossible to determine any expression which will present rationally the relation of these quantities to one another.

It is only possible to say that the value of the elastic or true coefficient of elasticity has been found to vary between 1,000,000 and 5,000,000 pounds per square inch, and that the ultimate tensile resistance varies from 100 to 500 pounds per square inch.

It will be seen later that it appears possible to connect the ultimate crushing resistance of concrete with the compressive coefficient of elasticity, and since it has previously been shown that the ratio between ultimate tensile and compressive resistance is about as 1:10, it may be possible to transpose to tension the empiric relations deduced in the compression experiments by in-

serting in those expressions, in the proper manner, the ratio of 1 to 10.

From the experiments that have been recorded so far, and from those which will be shown for compression, it may be said without much error that the coefficients for both tension and compression for any one mixture may always be taken equal. This will indicate the manner in which the ratio of 1 to 10 must be used.

Professor C. Bach of Stuttgart has made perhaps the most interesting and most reliable of experiments on the compressive elasticity of cement and cement mixtures. His experiments on the elasticity of concrete have been published in the "Zeitschrift des Vereines Deutscher Ingenieure" for April 27, 1895, and November 28, 1896.

The experiments recorded in the first issue mentioned were made by Professor Bach in July, 1894, on 32 cylinders with a circular cross section having a diameter of 9.9 inches and a height of 39.4 inches. Six different proportions of ingredients were used, and in general six specimens were made of each mixture, three with one brand of cement and three with another brand. The following table shows the mixtures employed, the parts being expressed by volume:

I. 1 cement, 2½ Neckar sand, 5 Neckar gravel.
II. 1 cement, 2½ Neckar sand, 5 limestone shingle.
III. 1 cement, 7½ natural gravel and sand mixed.
IV. 1 cement, 3 Neckar sand, 6 Neckar gravel.
V. 1 cement, 3 Neckar sand, 6 limestone shingle.
VI. 1 cement, 9 natural gravel and sand mixed.

The ends of the specimens were plastered with a layer of neat cement in order to facilitate planing. The specimens were taken from the moulds at the end of one day, and were then covered with bagging, which was kept moistened, for 28 days. At the time of testing the age of the specimens varied from 76 to 97 days.

The deformations were measured by means of a specially designed instrument reading directly to .00013 inch, on a measured length of about 29 inches. The load was applied to the specimens at a steady rate, from 0 to the point desired, in 1½ minutes, and the removal of the load was accomplished at the same rate.

In all of Professor Bach's experiments the loads were added and removed until it was found that there was no change in the

TABLE I.

Composition in Parts by Volume						Cement Used—Brand "B"				Cement Used—Brand "L"		
Cement	Sand from Neckar	Limestone Shingle	Neckar Gravel	Gravel and Sand Mixed	Age in Months	Specific Gravity	Coefficient of Elasticity Between Intensities of Stress of 0 and 113 Lbs. in Lbs. per Sq. In.	Ultimate Resistance in Lbs. per Sq. In.	Age in Months	Specific Gravity	Coefficient of Elasticity Between Intensities of 0 and 113 Lbs. in Lbs. per Sq. In.	Ultimate Crushing Resistance in Lbs. per Sq. In.
1	2½	—	5	—	2½	2.37	4,340,000	1370	2½	2.33	3,410,000	880
1	2½	5	—	—	2½	2.42	4,670,000	1780	2½	2.44	5,160,000	1520
1	2½	5	—	—	2½	2.42	5,340,000	1980	3	2.46	4,950,000	1580
1	2½	5	—	—	2½	2.43	4,730,000	1800	3	2.45	4,760,000	1615
1	—	—	—	7½	2½	2.39	4,870,000	1865	2½	2.33	3,820,000	1230
1	—	—	—	7½	3	2.42	4,970,000	2000	3	2.34	3,450,000	1200
1	—	—	—	7½	3	2.40	4,480,000	2090	3	2.35	3,480,000	1280
1	3	—	—	6	2½	2.39	4,470,000	1640	2½	2.37	3,920,000	1090
1	3	—	—	6	2¾	2.39	4,200,000	1560	3	2.38	3,680,000	1000
1	3	—	—	6	3	2.39	4,180,000	1700	3	2.38	3,910,000	1080
1	3	6	—	—	2½	2.43	4,910,000	1680	2½	2.46	4,170,000	1240
1	3	6	—	—	2½	2.43	4,640,000	1720	2¾	2.43	4,190,000	1360
1	3	6	—	—	3	2.42	4,470,000	1640	3	2.45	4,170,000	1230
1	—	—	—	9	2½	2.42	4,270,000	1510	2½	2.34	3,610,000	960
1	—	—	—	9	3	2.40	4,530,000	1660	3	2.33	3,250,000	908
1	—	—	—	9	3	2.41	5,170,000	1960	3	2.34	3,220,000	915

deformation as found by a previous reading. This required, in general, when the applied load was less than 570 pounds per square inch, four to eight repetitions; but with higher intensities of stress the deformations of the specimen were found to be also dependent on the time which the load remained on the specimen; that is, the strain was a function of both the load and the length of time the load was applied. This agrees with experiments made on some other materials, more notably those made by Pro-

TABLE II.

Parts by Volume				Ultimate Resistance to Crushing in Lbs. per Sq. In.		Specific Gravity	Coefficient of Elasticity in Lbs. per Sq. In. for a Compressive Stress Between the Limits of—		
				Length of Specimen					
Danube	Sand Egginger	Gravel from Danube	Broken Limestone Shingle	39.37 Inches	9.8 Inches		0-112 Lbs. per Sq. In.	0-560 Lbs. per Sq. In.	448-560 Lbs. per Sq. In.
	—	—	—	——	——	2.07	3,000,000	2,590,000	2,400,000
½	—	—	—	——	——	2.12	4,000,000	3,260,000	3,000,000
	—	—	—	2710	2460	2.04	3,300,000	2,560,000	2,290,000
½	—	—	—	1500	1810	1.95	2,260,000	1,670,000	1,370,000
	—	—	—	——	——	2.06	2,700,000	2,320,000	2,170,000
½	—	5	—	1620	1930	2.22	3,140,000	2,450,000	2,120,000
	2½	—	5	2270	——	2.36	4,218,000	3,610,000	3,080,000
½	—	—	5	——	2450	2.27	——	——	——
	—	6	—	1730	1750	2.23	3,000,000	2,370,000	2,140,000
	—	—	6	1940	——	2.34	3,850,000	2,980,000	2,550,000
	3	—	6	——	3080	2.34	——	——	——
½	—	7	—	1540	1630	2.23	2,490,000	2,030,000	1,820,000
½	—	—	7	1910	2640	2.32	3,580,000	2,830,000	2,450,000
	—	8	—	1450	1370	2.23	2,300,000	1,940,000	1,780,000
	—	—	8	1680	——	2.32	3,310,000	2,540,000	2,510,000
	4	—	8	——	2320	2.29	——	——	——
½	—	9	—	1310	1620	2.24	2,360,000	1,840,000	1,650,000
	4½	—	9	1410	2560	2.31	3,100,000	2,330,000	1,940,000
	—	10	—	1140	1240	2.21	2,220,000	1,710,000	1,440,000
	5	—	10	1460	1830	2.31	3,400,000	2,400,000	1,980,000
	1½	—	3 (Finely broken)	——	3790	2.32	——	——	——
	1½	3	—	——	3250	2.27	——	——	——
	2	—	4 (Finely broken)	——	3380	2.34	——	——	——
	2	4	—	——	2900	2.30	——	——	——

fessor Thurston. This question is of the greatest interest in connection with the fatigue of materials. Table I. shows the results obtained.

The second set of experiments, which were recorded by Professor Bach in the issue of the 28th of November, 1896, were made on two sizes of round cylindrical specimens, the first being 39.4 inches high, with a diameter of 9.9 inches, and a consequent cross section of 77½ square inches; the second being cylinders of the same cross section, but only 9.9 inches high. The experiments on the elasticity of the material were made only on the larger specimens, the deformations being measured on a length of about 29½ inches, by the same instrument noted before, reading directly to .00013 inch. Loads were applied at intervals of 112 pounds per square inch. The average age of the specimens at the time of testing was about three months. The concrete was prepared as nearly as possible in the same way as in the case of actual construction work; water was added in such quantities that by ramming the whole mass appeared very plastic.

Table II. shows in detail the proportions of the mixtures employed and the number of specimens tested, the total number being 102.

The sand marked "Egginger" was quartz sand with a little feldspar, while the "Danube" sand was river sand. It will be seen that in almost all cases the concrete in which the stone was a limestone attained a higher ultimate resistance to crushing. It would seem, then, that the gravel concrete should be the more elastic; that is to say, it should yield more under stress than the limestone concrete; the table shows this to be so. Table II. also shows clearly the increase and decrease in the coefficient of elasticity with the variation of cement in the mixtures.

Figure 1 is plotted from the results of the table and shows the variation in the coefficient of elasticity with varying proportions of cement to other aggregates. In the case of mortar, it will be seen that the coefficient rises from the neat cement to a mortar of one cement to one sand, and then slowly drops until, with a mixture of one cement to three and one-half sand, it is about the same as that for neat cement. The results as plotted for the

periments by Hartig, in "Civil Ingenieur," 1893, page 467, and Baker, in "Civil Ingenieur," 1894, page 718, as furnishing results corroborating the variation of the elasticity as found by him.

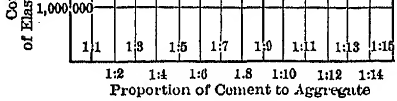


FIG. 1.—BACH'S TESTS.

The coincidence in the rise of the values of the coefficient of

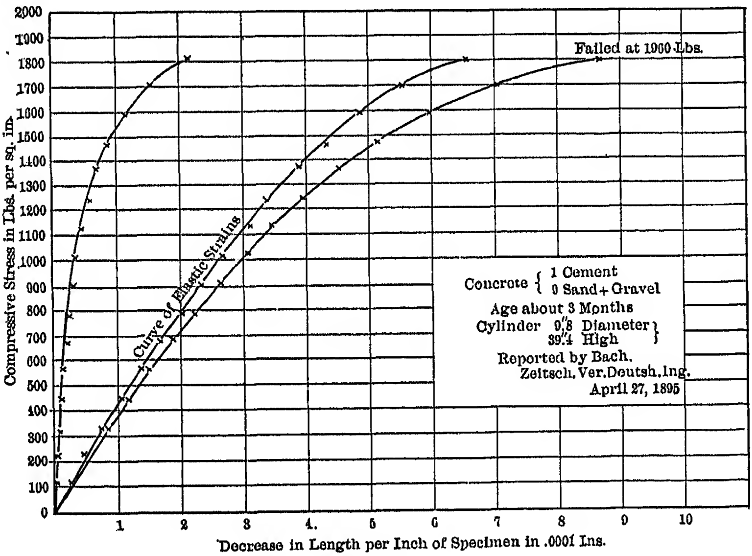


FIG. 2.

elasticity as compared to the increase in the specific gravity of the material is worth noting, and the table shows clearly that in-

creased power to resist distortion accompanies higher specific gravities.

Figure 2 is the only stress-strain diagram inserted illustrative of Professor Bach's results, because it is so thoroughly characteristic of all the results obtained. It shows completely the behavior of the material almost to the point of failure. The elastic strain curve differs but little from a straight line for the first half of its length; and that this curve never shows great departures may be seen from the following average values of the coefficient of elasticity which Professor Bach has deduced from the preceding experiments:

Mixture as Given by Column Headed "Specimen Mark" in Table II.	Stress-Strain Relation, Expressed in Lbs. per Sq. In., from Equation $E=\frac{p^n}{l}$
I., V. .... Neat Cement	$3{,}556{,}000=\frac{p^{1.09}}{l}$
II. .... 1:1½ Mortar	$5{,}050{,}000=\frac{p^{1.11}}{l}$
III. .... 1:3 Mortar	$4{,}480{,}000=\frac{p^{1.15}}{l}$
IV. .... 1:4½ Mortar	$3{,}270{,}000=\frac{p^{1.17}}{l}$
VI* .... 1:2½:5 Concrete	$4{,}230{,}000=\frac{p^{1.14}}{l}$
VIII* .... 1:3:6 Concrete	$3{,}980{,}000=\frac{p^{1.14}}{l}$
XVI* .... 1:5:10 Concrete	$3{,}080{,}000=\frac{p^{1.16}}{l}$
VII† .... 1:2½:5 Concrete	$6{,}500{,}000=\frac{p^{1.16}}{l}$
IX† .... 1:3:6 Concrete	$5{,}400{,}000=\frac{p^{1.16}}{l}$
XVII† .... 1:5:10 Concrete	$5{,}210{,}000=\frac{p^{1.21}}{l}$

*Gravel Concrete. †Limestone Concrete.

Size of Specimen	Crushing Load in Lbs. per Sq. In.	Average Modulus of Elasticity in Lbs. per Sq. In.
1 Inch Cube	5896	——
2 " "	7094	——
3 " "	5937	——
4 " "	4847	——
5 " "	4610	——
6 " "	4283	——
7 " "	4987	——
8 " "	5007	1,358,774
9 " "	4754	1,421,111
10 " "	4761	1,510,416
11 " "	5374	1,703,877
12 " "	5291	1,635,107
4 x 4 x 1	16471	——
4 x 4 x 2	6370	——
4 x 4 x 3	6003	——
8 x 8 x 2	10664	——
8 x 8 x 3	7186	——
8 x 8 x 4	5952	——
8 x 8 x 5	6019	——
8 x 8 x 6	5771	——
12 x 12 x 2	Tested in built-up piers, set dry. Results not comparable.	——
12 x 12 x 4		——
12 x 12 x 6		——
12 x 12 x 8		——

imit, although not a precise one, below which the stress-strain relation may be expressed by a constant.

General Q. A. Gillmore treats very extensively of the compressive resistance and elasticity of Portland and natural cement mixtures in his book, "Notes on the Compressive Resistance of Free Stone," etc., published in 1888. The accuracy of the tests appears to be insured, since they were all made at the Watertown Arsenal.

In the case of the neat cement experiments, abstracted in Table III., a series of cubes and prisms was made of Dyckerhoff Portland cement, the average age of the specimens at the time of testing being one year, ten and one-half months. The cubes varied in sizes, by increments of one inch, from one to twelve inches on the side, there being six samples of each size. The majority of the specimens which were tested, including both the cubes and prisms, had plastered faces, the exceptions being a few of the 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 inch cubes. It should be noted that plastering the compressed surfaces uniformly increases the ultimate resistance.

It will be seen that in the case of the cubes the smaller cubes gave slightly higher crushing resistances than the others; that in the case of the prisms the very flat prisms furnished extremely high values. This is to be expected. It will be seen that the average value is about 5,000 pounds per square inch. The coefficient of elasticity was determined for the larger cubes, and in calculating these values General Gillmore divided the unit stress at a point which he names the elastic limit by the unit deformation, no deduction being made for permanent set; these coefficients, therefore, are not the true elastic coefficients; they would be greater than given in the table.

Figure 3 shows the stress-strain curve determined for one 10-inch cube, and also for one 12-inch cube. The curves are characteristic of all the tests, although some show a slight convexity to a horizontal line at the origin. This may possibly be due to the squeezing out of the plaster between the specimen and the bed plate, since it seems that the deformations were measured between the heads of the testing machine. The majority of the curves shown by General Gillmore are, however, very similar to Figure 3. The elastic limit might be placed at .6 to .75 of the ultimate resistance.

Table IV. gives the values of the ultimate resistance obtained by General Gillmore for mortar and concrete cubes mixed with three different brands of cement—two natural and one Portland. Each result shown is an average of two specimens, the beds of all specimens being plastered before being tested. Some of the

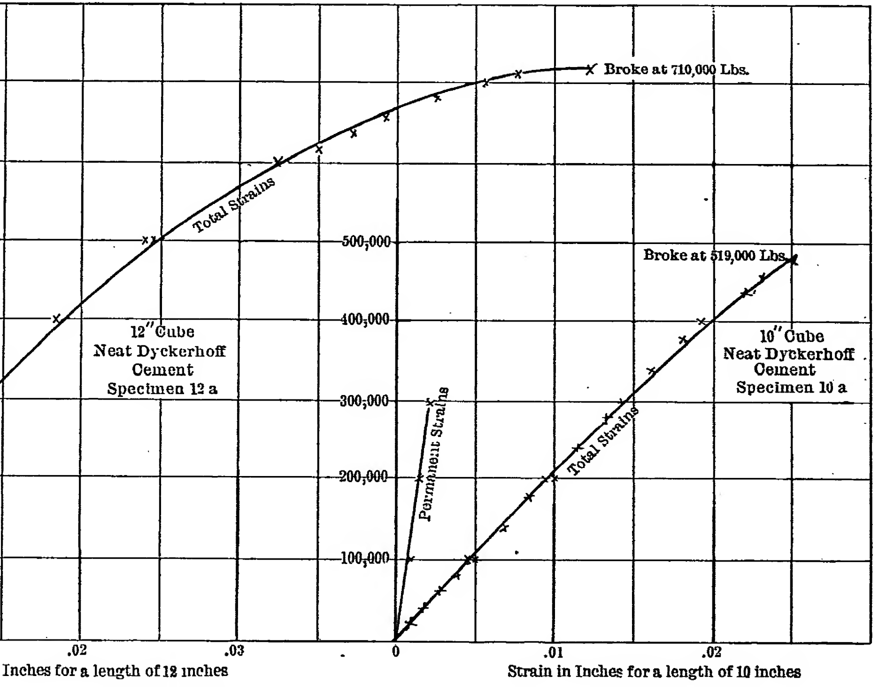


FIG. 3.—FROM GILLMORE'S TESTS.

cubes were, in addition, placed between wooden pine cushions, but it was invariably found that the use of these wooden cushions did not develop the full possible strength of the material.

In the table as given no distinction has been made between specimens, whether they were provided with such cushions or not. The coefficient of elasticity could only be determined for

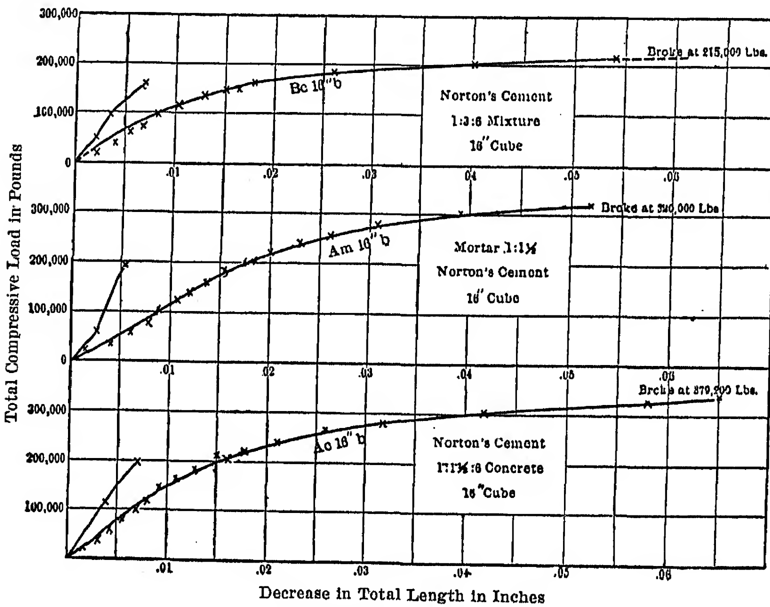


FIG. 4.—FROM GILLMORE'S TESTS.

those specimens in which no wooden blocks were used, because the deformations were measured directly between the heads of the testing machine and the concrete was forced rather deeply into the wooden cushions.

The values shown have this peculiarity: that the concretes seem to possess, on the whole, a greater strength than the mortars, which is rather exceptional, and can perhaps be explained only by the fact that the mixtures were better balanced.

Table V. shows the values of the coefficients of elasticity of the larger size cubes, determined in the same manner as in the

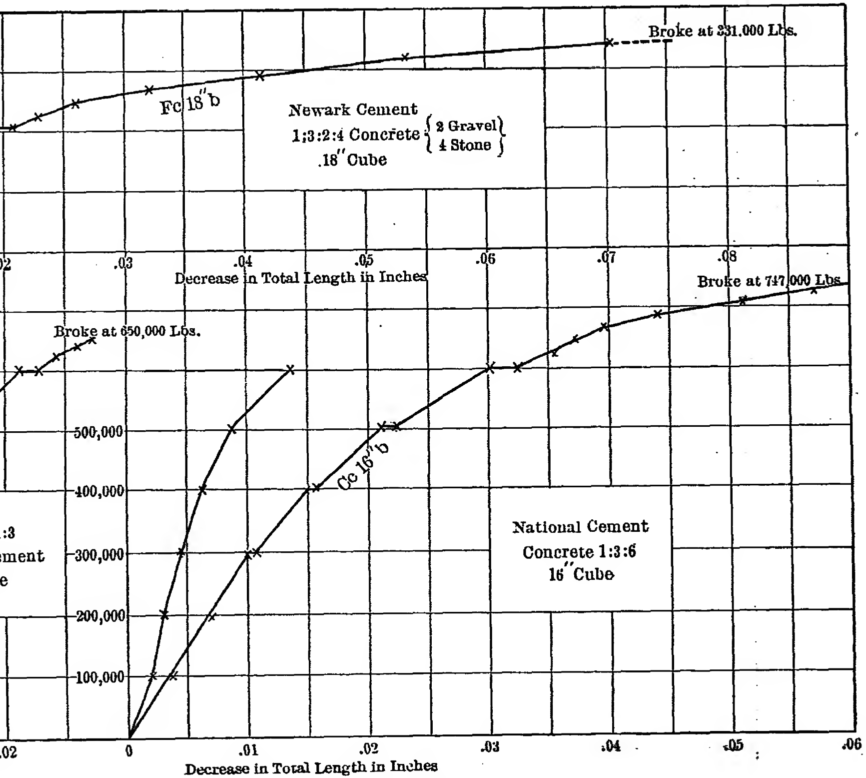


FIG. 5.—FROM GILLMORE'S TESTS.

case of the neat specimens of Table III. The intensity of stress for which these coefficients are calculated is shown.

Figures 4 and 5 are characteristic stress-strain curves of all the mortar and concrete tests. It will be seen that there is a point which might be called the elastic limit, although all the

TABLE IV.

Brand of Cement	Composition of Specimen Parts by Volume: Cement	Sand	Gravel	Broken Stone	Size of Specimen Cubes: 2 In.	4 In.	6 In.	8 In.	10 In.	12 In.	14 In.	16 In.	18 In.
					Ultimate Compressive Resistance in Lbs. per Sq. In.								
A....	I (Dry Meas.)	3	–	–	1429	758	800	707	945	685	715	612	—
"....	"	3	2	4	—	1032	1127	1035	1167	972	723	856	941
B....	I (Paste)	1½	–	–	—	2042	1340	1746	—	1346	—	1247	—
"....	"	3	–	–	—	1324	750	790	—	688	—	718	—
"....	"	1½	–	6	—	2322	963	1434	—	1560	—	1447	—
"....	"	3	–	6	—	1633	1000	861	—	765	—	843	—
C. ..	"	3	–	–	—	3450	2655	2469	—	2434	—	2519	—
"....	"	3	–	6	—	4014	2629	3025	—	2690	—	2978	—

A—Newark Co.'s Rosendale; tested at age of about 22 months.
B—Norton's Natural; tested at age of about 3 years and 10 months.
C—National Portland; tested at age of about 3 years and 10 months.

specimens show considerable permanent deformations at fairly low stresses. This elastic limit might be taken between two-thirds and three-quarters of the ultimate resistance. None of

TABLE V.

Brand of Cement	Composition of Specimens: Cement	Sand	Stone	Size of Specimen, Cube: 8 In.	10 In.	12 In.	16 In.	18 In.	Determined at an Intensity of About: Lbs. per Sq. In.
				Coefficient of Elasticity in Lbs. per Sq. In.					
Newark Rosendale ..	1	3	2 Gravel, 4 Stone	—	549,000	465,000	572,000	567,000	650
Norton's Nat..	1	1½	—	—	—	614,000	655,000	—	750
"	1	3		—	—	573,000	484,000	—	410
"	1	1½	6	—	—	708,000	778,000	—	800
"	1	3	6	—	—	702,000	530,000	—	500
National Port.	1	3	—	1,092,000	—	1,606,000	1,864,000	—	1800
" "	1	3	6	1,076,000	—	1,350,000	1,732,000	—	1500

the curves show the coefficient to be a constant quantity, and not much error is introduced if it is taken constant below the assumed elastic limit.

220	90	1	2	4	A	2	Air dry	140	4,421,000	1243	Dry	
221	90	1	2	4	"	2	"	144	5,792,000	982	"	
80	—	1	2	5	"	2	"	146	3,927,000	726	"	
272	60	1	3	6	"	2	Air	—	2,886,000	413	Very dry	
225	30	1	2	4	"	1½	"	160	7,171,000	3020	Plastic	
226	30	1	2	4	"	1½	Water	152½	4,625,000	2610	"	
76	9	1	2	5	"	1½	Air	152	4,930,000	423	"	
248	32	1	2	5	"	1½	"	151	5,055,000	2097	"	
249	32	1	2	5	"	1½	Water	154½	7,292,000	2830	"	
250	34	1	3	6	"	1½	Air	143	5,104,000	1310	"	
251	39	1	3	6	"	1½	"	146	7,520,000	1733	"	
252	39	1	3	6	"	1½	Water	152	6,646,000	2242	"	
253	38	1	4	8	"	1½	"	143	4,560,000	1282	"	
291	90	1	—	—	M	—	"	136	6,578,000	5280	"	Sudden Failure
292	90	1	—	—	"	—	Air	129	3,940,000	4580	"	
254	38	1	4	8	A	1½	"	139	2,446,000	617	Excess	
255	38	1	4	8	"	1½	"	138	2,247,000	797	"	

CINDER CONCRETE.

49	7	1	2	4	A	—	Water	120	514,000	—	—	—
50	7	1	2	4	"	—	Air	116	876,000	—	—	—
48	7	1	2	4	"	—	"	111	945,000	—	—	—
152	30	1	2	4	"	—	Water	119	1,358,000	993	—	—
153	30	1	2	4	"	—	Air	112	1,626,000	1049	—	—
154	30	1	2	4	"	—	"	106	1,399,000	976	—	—
189	30	1	2	5	"	—	"	109	1,772,000	941	—	—
190	30	1	2	5	"	—	Water	114	1,021,000	705	—	—
138	60	1	2	5	"	—	Air dry	114	1,055,000	573	—	—
139	60	1	2	5	"	—	"	116	1,783,000	847	—	—
140	60	1	2	5	"	—	"	119	1,152,000	670	—	—
163	30	1	2	5	"	—	Water	114	1,168,000	682	—	—
216	60	1	3	6	"	—	Air dry	107	917,000	734	—	—
217	60	1	3	6	"	—	"	101	916,000	544	—	—
192	30	1	3	6	"	—	Air	—	1,473,000	484	—	—
193	30	1	3	6	"	—	"	107	1,447,000	511	—	—
194	30	1	3	6	"	—	Water	118	751,000	500	—	—
218	30	1	3½	7	"	—	A r	106	533,000	405	—	—

A—Atlas Cement; M—Medusa Cement.

It will be seen that the ultimate compressive resistance decreases very uniformly as the percentage of materials other than cement in the mixture increases, and, also, that the modulus of elasticity increases with the ultimate resistance. The compressive resistance of the neat cement cubes is about 5,000 pounds per

square inch and reduces to about 1,000 pounds for a 1:4:8 mixture. These compressive resistances have been plotted in the usual manner in Figure 6 and the results averaged by means of

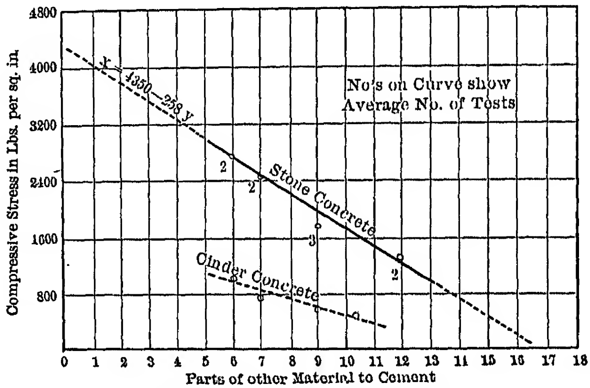


FIG. 6.—FROM HENBY'S TESTS.

a straight line, which may be expressed algebraically by the following equation:

$$x = 4350 - 258y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

For Eq. (1), then, it will be seen that a neat cement mixture

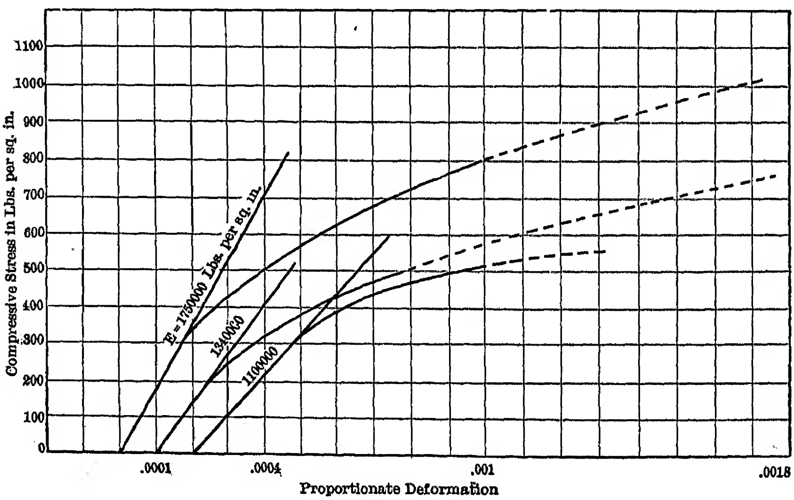


FIG. 7.—FROM HENBY'S TESTS.

be considered to be one-half of the ultimate resistance.

From an examination of the coefficients of elasticity determined by Henby it is impossible to check Bach's proposition that there is some mixture which attains the highest value of the coefficient, and that mixtures either leaner or richer have de-

TABLE VII.

Brand of Cement	Mixture	Average Compressive Strength, Lbs. per Sq. In.	Coefficient of Elasticity in Lbs. per Sq. In. Between Loads of 100 and 600 Lbs. per Sq. In.
Germania Portland..	1:1:3	2001	——
" " ..	1:2:3	1634	——
" " ..	1:2:4	1325	——
" " ..	1:2:5	1084	——
" " ..	1:3:6	788	——
Alpha Portland.....	1:1:3	2834	2,500,000
" "	1:2:5	1600	1,279,000
Atlas "	1:1:3	2414	3,125,000
" "	1:2:5	1223	1,138,000

creasing values. In these experiments the value of the coefficient decreases rather uniformly as the mixtures become more lean.

Table VII. is taken from the Watertown Arsenal Report for 1898, and shows results of tests made on cinder concretes for the Eastern Expanded Metal Company of Boston. In all 84 twelve-inch cubes of various ages, made with different brands of cement, were tested. Only the results of the better known brands are here abstracted, and only those which reached the age of about three months. Each result shown is an average of three tests. The cinder used was in the condition in which it came

from the furnace; it was not sifted, and only the larger clinkers were broken.

In the same Watertown Arsenal Report for 1898 are also recorded results of tests on 95 cubes and prisms which were manufactured at the Arsenal. Only those specimens in which Alpha cement was used are shown in Table VIII., the mixtures being 1:1:3. The sand was bank sand, the pebbles were from the Ar-

TABLE VIII.—12-INCH CUBES—1:1:3 ALPHA CEMENT.

Kind of Stone	Ultimate Compressive Resistance in Lbs. per Sq. In. at Age of—		Coefficient of Elasticity in Lbs. per Sq. In. Bet Loads of 100 and 600 Lbs. per Sq. In. at Age of—	
	About 1 Month	About 2 Months	About 1 Month	About 2 Months
Trap ½ Inch	2800	5021	3,571,000	4,167,000
" ¾ "	3200	——	8,333,000	——
" 1 "	4917	5272	6,250,000	8,333,000
{Trap ½ Inch....1 Part " 2½ " ....2 Parts}	4349	4544	8,333,000	6,250,000
{" 2½ " ....1 Part " 1 " ....1 " " ½ " ....1 "}	4800	5542*	8,333,000	8,333,000
Pebbles ⅜ Inch	2992	3870	4,167,000	3,125,000
{Trap 2½ Inch....2 Parts Gravel ⅛ Inch...1 Part}	5024	4700	6,250,000	12,500,000
Pebbles 1½ Inch	3817	4018	4,167,000	2,778,000
{Pebbles ⅜ " ..1 Part " 1½ " ..2 Parts}	3800	3490	4,167,000	5,000,000
{Gravel ⅛ Inch....1 Part " ⅜ " ....1 " Pebbles 1½ Inch..1 "}	3000	3800	3,125,000	3,125,000
Trap 2½ Inch	4140	4523	5,000,000	12,500,000
{Trap 2½ Inch....1 Part Pebbles ⅜ Inch...1 " Gravel ⅛ Inch....1 "}	2700	——	4,167,000	——
Mixture 1:3:6 of 1 In. Trap	2190	——	3,125,000	——
Pebbles 1½ In. to 3 In.	3800	——	4,062,000	——
Trap 1½ Inch	3572	——	5,208,000	——
1:1 Mortar	4400	4800	5,000,000	6,250,000
Neat Alpha Cement	5551*	——	5,000,000	——

*Not fractured.

senal grounds and the rock was broken trap of different sizes from Waltham, Mass. The ¾ inch stone all passed a ¾ inch sieve and was all retained on the next smaller size, viz., ½ inch. The other graded sizes were obtained in a similar manner. The ages of the specimens varied from 7 to 76 days; only those having an

"	1	4	12	1,403,000	1,382,000	2226
"	1	5	15	1,370,000	1,300,000	1842
"	1	6	16	1,087,000	———	1365
"	1	1	4	1,628,000	1,508,000	3330
"	1	2	6	2,263,000	2,081,000	2519
"	1	3	8	1,745,000	1,580,000	2567
"	1	4	11	1,801,000	1,499,000	2094
Wayland	1	1	5	1,822,000	1,749,000	4165
"	1	2	7	2,314,000	2,002,000	3221
"	1	3	9½	2,018,000	1,721,000	2311
"	1	4	12½	1,528,000	1,432,000	1851
"	1	5	15	1,427,000	1,273,000	1713
"	1	1	4½	3,072,000	2,265,000	4031
"	1	2	6½	2,285,000	1,991,000	3465
"	1	3	8	1,845,000	1,555,000	2230
"	1	4	11	1,449,000	1,218,000	1843
"	1	5	12	1,318,000	1,100,000	1723
Ironclad	1	2	7½	2,518,000	2,295,000	2852
"	1	3	10	1,752,000	1,227,000	1927
"	1	4	15	1,408,000	———	1665
"	1	2	6½	3,273,000	2,937,000	3678
"	1	3	8½	2,168,000	1,757,000	2296
"	1	4	11	1,792,000	1,468,000	1880
Empire	1	2	7	2,874,000	2,505,000	3521
"	1	3	10	2,292,000	1,890,000	2460
"	1	4	13	1,608,000	1,266,000	1774
"	1	2	6½	2,685,000	2,446,000	3579
"	1	3	8	2,609,000	2,176,000	2545
"	1	4	10½	2,081,000	1,622,000	1899
Champion	1	1	5	2,781,000	2,253,000	2928
"	1	2	7	2,609,000	2,207,000	2459
"	1	3	9	1,528,000	1,046,000	1495
"	1	1	4	2,780,000	2,571,000	3127
"	1	2	5½	2,516,000	2,228,000	2377
"	1	3	8	1,602,000	———	1393

nen only. It will be seen that the values of the coefficient of lasticity are very high. This may be explained by the density of the specimens, which averaged about 150 pounds per cubic

foot; whereas, in the tests made by Rafter, and to be noted la the average weight was only about 140 pounds per cubic foo

Table IX. is taken from the Watertown Arsenal Report for 1898 and records experiments made for Mr. George W. Rafter on twelve-inch cubes of concrete made with various brands of cement. Mr. Rafter's tests are explained in greater detail on page 121 et seq.; here are only given the experiments concerning the elasticity. average age of the specimens was about one year, seven one-half mon The majority results are a ages of te made on two four specim no distinc has been drawn between dry, plastic or excess. The gau length on which the elastic properties were measured was inches. The experiments are tabulated in the order of the richness of the various mixtures.

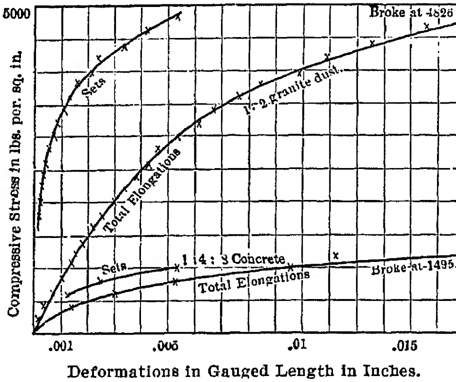


FIG. 8.

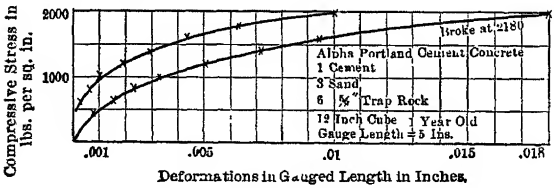


FIG. 9.

It will be seen, in general, that the values of the modulus of elasticity decrease with the leanness of the mixture. The ultimate crushing resistance also decreases

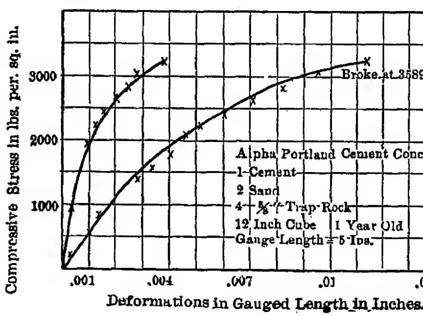


FIG. 10.

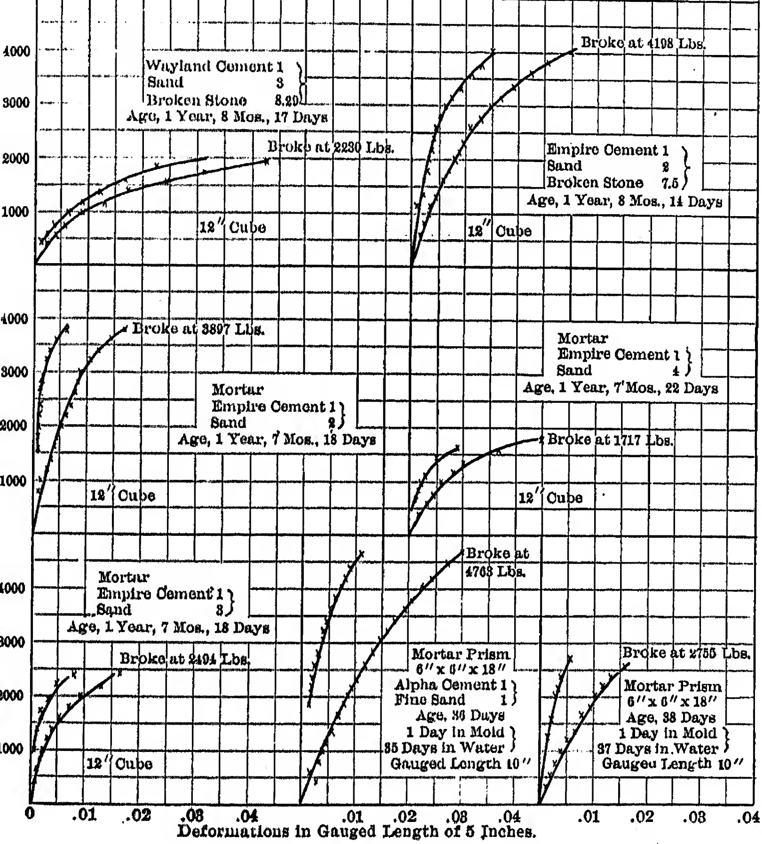

4000
3000
2000
1000
Wayland Cement 1
Sand 3
Broken Stone 8.20
Age, 1 Year, 8 Mos., 17 Days
Broke at 2230 Lbs.
12″ Cube
Broke at 4198 Lbs.
Empire Cement 1
Sand 2
Broken Stone 7.5
Age, 1 Year, 8 Mos., 14 Days
12″ Cube
Broke at 3897 Lbs.
Mortar
Empire Cement 1
Sand 2
Age, 1 Year, 7 Mos., 18 Days
12″ Cube
Mortar
Empire Cement 1
Sand 4
Age, 1 Year, 7 Mos., 22 Days
Broke at 1717 Lbs.
12″ Cube
Mortar
Empire Cement 1
Sand 3
Age, 1 Year, 7 Mos., 18 Days
Broke at 2494 Lbs.
12″ Cube
Broke at 4763 Lbs.
Mortar Prism
6″ x 6″ x 18″
Alpha Cement 1
Fine Sand 1
Age, 36 Days
1 Day in Mold
35 Days in Water
Gauged Length 10″
Broke at 2755 Lbs.
Mortar Prism
6″ x 6″ x 18″
Age, 38 Days
1 Day in Mold
37 Days in Water
Gauged Length 10″
0 .01 .02 .03 .04 .01 .02 .03 .04 .01 .02 .03 .04
Deformations in Gauged Length of 5 Inches.

FIG. 11.

with the leanness of the mixture; in other words, the modulus of elasticity is some function of the ultimate crushing resistance.

Table IX. also shows that the modulus is not a constant quantity for any one specimen. The values given are calculated between two increments of stress, from 100 to 600 pounds and from 100 to 1,000 pounds per square inch. In every instance the values for the second increment of stress are smaller.

Figures 8 to 12 are all abstracted from the Watertown Arsenal Report for 1898 and 1901, and show clearly the elastic behavior of some of the mixtures which have been tabulated on the

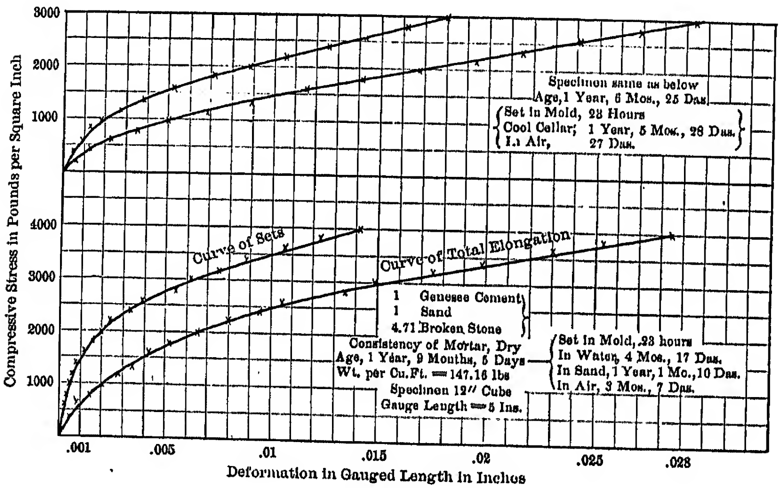


FIG. 12.

preceding pages. Two curves are shown, the one to the right being the curve of total deformation and the other the curve of sets. The curves are characteristic of all the tests made, and inspection tends to confirm the opinion that concrete mixtures in compression have a point which might be called the elastic limit, at about 5-10 or 6-10 of the ultimate crushing resistance. In the case of the neat cements or mortars, this elastic limit approaches more closely to the ultimate resistance, having a value of perhaps 8-10 of it.

Professor E. J. McCaustland records in the Transactions of

the American Society of Civil Engineers, 1903, some experiments which he made on concrete and mortar columns of various compositions and of various ages, and for which he determined the true coefficient of elasticity at 500 pounds per square inch.

Table X. shows the results of his tests on these columns, which were circular, 10 inches in diameter and 40 inches long. It will be seen that the coefficients varied, although not uniformly, with the variation in the ultimate compressive resistance, and, from the stress-strain curves which are shown in the original paper, the material might be said to have an elastic limit of 5-10 to 6-10 of the ultimate resistance.

TABLE X.

Proportions			Age in Months	Coefficient of Elasticity in Lbs. per Sq. In.	Ultimate Crushing Strength Lbs. per Sq. In.	
Cement	Sand	Broken Stone				
1	2	3	14	1,050,000	1000	
1	2	3	11	1,530,000	1752	1654
1	2	3	13	3,060,000	1215	
1	2	3	14	2,010,000	2650	
1	3	4	10	1,100,000	1484	
1	3	4	11	1,380,000	1382	1411
1	3	4	14	1,425,000	1230	
1	3	4	11	1,441,000	1550	
1	3	5	14	1,450,000	1550	
1	3	5	14	——	1500	1504
1	3	5	14	1,531,000	1792	
1	3	5	14	1,050,000	1170	
1	2	5	15	840,000	1045	
1	2	5	15	1,510,000	1955	1532
1	2	5	14	1,372,500	1450	
1	2	5	23	——	1680	
1	4	—	23	2,775,000	2660	
1	2	—	23	4,625,000	3410	
1	3	—	23	3,700,000	2250	

Figure 13 presents the results of compressive experiments reported by Professor Edgar Marburg to the American Society for Testing Materials, at its annual meeting, 1904. These stress-strain diagrams represent tests on four 6x6-inch prisms, 24 inches long; the deformations were measured on a gauge length of 18.5 inches. The concrete was composed of 1 part of Delaware River bar sand, to 2 parts of Atlas Portland Cement, to 4 parts of $\frac{3}{4}$-inch broken trap rock; the materials were mixed rather wet. The age

of the specimens, all being stored in air, was 30 days, and the average weight 154 pounds per cubic foot.

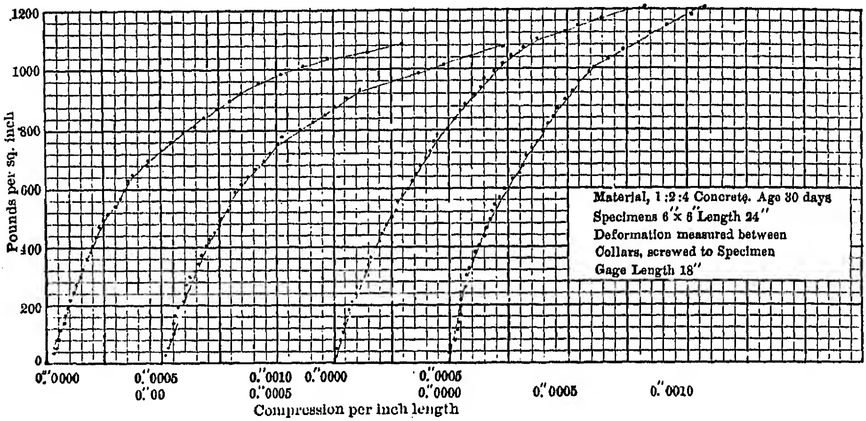


FIG. 13.—MARBURG'S TESTS.

The figure shows the stress-strain curve to be sensibly a straight line to a point about one-half the ultimate resistance.

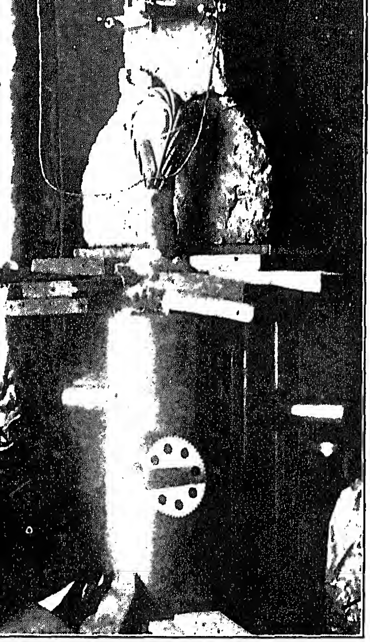
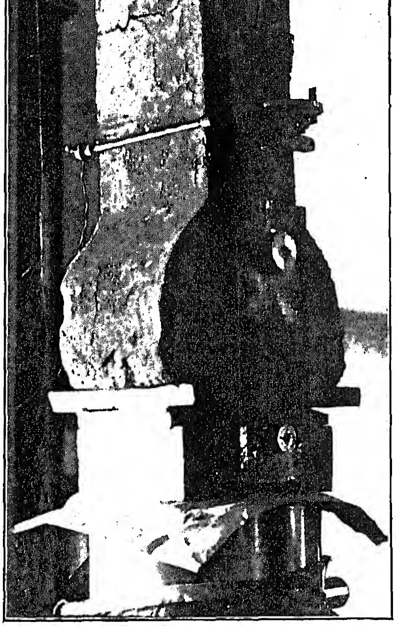
The values of the compressive coefficient of elasticity, calculated without reference to any permanent set occurring in connection with the applied stresses, are given in the following table; the specimens in the figure are numbered from left to right:

TABLE XI.

Specimen No.	Ultimate Compressive Resistance in Lbs. per Sq. In.	Coefficient of Elasticity in Lbs. per Sq. In.	Determined for Stresses of—
1	1166	2,000,000	0—500 Lbs. per Sq. In.
2	1154	2,000,000	0—500 " "
3	1277	2,300,000	0—500 " "
4	1316	2,700,000	0—600 " "

It is seen that the coefficient increases with the ultimate resistance.

Professor Marburg also furnishes the average ultimate compressive resistance of nineteen 6-inch cubes of the same materials and same age, but taken from batches mixed at various times. The value given is 1643 pounds per square inch. Two specimens,

Enlarged Views of Figures Opposite Page 86.
he Location of the Points of Fracture, as Well as Details of the Extensometer, Are Clearly Shown.

little more moist than damp earth; in plastic blocks, in which the mortar was like that used by masons; and in blocks, in which the water was in excess, so that the concrete quaked like liver under moderate ramming. From every batch mixed in one of these ways four specimens were prepared and stored differently. One block was placed in water from the time of making (summer of 1896) until December 1, 1896, then buried in sand until January 10, 1898, when it was shipped from the place of manufacture to the Watertown Arsenal in Massachusetts. The second block stood in a cool cellar until shipment; the third block was exposed to the weather, and the fourth block was covered with burlap and was wet with water several times a day until November 1, 1896, after which it took the weather as it came until the day of shipment. The tests were made with Portland cement only. The sand was hand-broken Portage sandstone passing through a two-inch ring.

Examination of these detailed experiments shows that the four specimens of any one series treated to the various conditions of weather gave rather uniform results; at least, it cannot be noticed that any one condition shows radically worse effects than any other. In further considering these experiments, therefore, the average of the four specimens prepared at any one time will be used.

Mr. Rafter does not express the ingredients of a concrete mixture in the usual way, such as one part of cement to three of sand, to three of stone, either by weight or measure; but he expresses the relations, in percentages, between a definite mortar,

say, 1:3, to a unit weight of stone. In order to make his results comparable to others the following table has been prepared, which expresses roughly Mr. Rafter's nomenclature in the more

Percentage of Mortar	Ratio of Cement to Sand in the Mortar					
	1:1	1:2	1:3	1:4	1:5	1:6
33	1:1:5	1:2:7	1:3:9½	1:4:12	1:5:15	1:6:16½
40	1:1:4	1:2:6	1:3:8	1:4:10½	1:5:12	

usual terms. Two percentages of mortar to stone were used, 33 per cent. and 40 per cent., and six different mortars, varying from 1:1 to 1:6.

TABLE I.

Consistency of Mortar	Parts of Cement to Sand	Percentage of Mortar to Stone	Ultimate Crushing Strength in Lbs. per Sq. In. Average of 4 Specimens
Excess of Water	1:1	33%	3764
" "	1:2	"	2847
" "	1:3	"	1723
" "	1:4	"	1767
" "	1:5	"	1441
Dry	1:1	"	4267
"	1:2	"	2888
"	1:3	"	2056
"	1:4	"	1810
"	1:5	"	1537
Plastic	1:1	"	4072
"	1:2	"	2777
"	1:3	"	2207
"	1:4	"	1600
"	1:5	"	1586
Excess of Water	1:1	40%	3256
" "	1:2	"	3168
" "	1:3	"	2016
" "	1:4	"	1670
" "	1:5	"	1400
Dry	1:1	"	3966
"	1:2	"	3404
"	1:3	"	2179
"	1:4	"	1671
"	1:5	"	1559
Plastic	1:1	"	4123
"	1:2	"	2960
"	1:3	"	2027
"	1:4	"	1750
"	1:5	"	1465

It will be seen, for instance, that the concrete known as 1:3 mortar, 40 per cent. may be expressed as a 1:3:8 concrete.

TABLE II.

Plasticity of Mortar	Amount of Mortar		Strength of the 40% Concrete in Terms of That of the 33%
	33%	40%	
	Crushing Strength in Lbs. per Sq. In.		
Dry....................	2408	2532	105%
Plastic................	2259	2329	103%
Excess................	2133	2227	104%
Mean.................	2267	2363	104%

It will be seen, therefore, that the effect of plasticity is not of great importance; in practice, what little gain in strength the dry mixed specimens may show is negligible in the face of other considerations, the principal one being the increased cost of manufacture of dry over the wet concretes. This is due to the extra cost of the ramming required.

TABLE III.

Proportions in the Mortar	Amount of Mortar		Strength of the 40% Concrete in Terms of That of the 33%
	33%	40%	
	Crushing Strength in Lbs. per Sq. In.		
1 Cement:2 Sand......	2640	2820	107%
1 Cement:3 Sand......	1893	1905	102%
1 Cement:4 Sand......	1684	1689	100%

Table III. shows that there is but very little increase in strength of the 40 per cent. concretes as compared to the 33 per cent. This may possibly be explained by the fact that in the 33 per cent. specimens the mortar did not entirely fill the voids in the stone; the stones therefore had direct bearing on each other, while in the

40 per cent. concrete the voids were just about filled; the strength of the mortar itself in that case had less influence than the direct bearing of the stones on each other in the first instance.

Mr. Rafter's method of determining the proportions of the ingredients in the mixture is open to criticism. The densest concrete is formed when the sand grains fill as many voids as possible in the stone, and the cement grains then fill as many as possible of the remaining voids in the stone-sand mixture. This is different from first filling the voids in the sand with cement and then the voids in the stone with mortar. In the latter case

TABLE IV.

Brand of Cement	Cement to Sand by Measure	Percentage of Mixed Mortar to Broken Stone	Ultimate Crushing Strength in Lbs. per Sq. In.
Wayland Portland.......	1:1	33%	3154
" "	1:2	42%	2454
" "	1:3	42%	1720
" "	1:4	42%	1363
" "	1:6	33%	1431
" "	1:1	——	4381
" "	1:2	——	2409
Saylor's Natural........	1:1	42%	2978
" "	1:2	42%	1890
" "	1:3	42%	1542
" "	1:4	42%	1132
" "	1:5	42%	1087
" "	1:6	42%	729
" "	1:2	——	2550

the voids in the sand will usually be found to be greater than the sum of the voids in the stone-sand mixture.

Table IV. is taken from the Report of the State Engineer of New York for 1894, and records experiments which were made by Mr. George W. Rafter previous to those just tabulated. These tests were made on 174 concrete cubes of one cubic foot each whose average age was three months. The stone which was used was hard quarry stone, broken to pass a two-inch ring and was washed clean. Each result shown is an average obtained from two to six specimens. Some of the blocks were placed in water after the final set had taken place. The result obtained from such blocks was averaged in with others in the table, it being found almost uniformly, however, that the ones which

Cement	Sand	Gravel	Stone	30 Days	7 Months	1 Year
1	1½	—	4	1448	2213	2917
1	3	—	7½	1024	1987	2076
1	2	3	4	1096	2180	2094
1	2	7	—	746	1633	1792
1	2¼	8	—	739	1540	1448

1901, and shows the ultimate compressive resistance, at various ages, of 12-inch concrete cubes made from one brand of cement. Each result shown is an average of three tests. It will be seen that this concrete did not gain in strength after seven months.

Tables VI. and VII. are taken from the same Report; the former shows the ultimate crushing strength of concrete prisms

TABLE VI.

Composition			Number of Specimens Tested	Ultimate Crushing Strength in Lbs. per Sq. In.
Cement	Sand	Stone		
1	2½	4—½ In. to 2 In. Diam. Pebbles	8	2326
1	2½	4—¼ In. to 2½ In. Diam. Gravel	6	3363
1	2½	4—1 In. to 2½ In. Diam. Hard Trap Rock	6	3886

6x6x36 inches in length, pressed on their ends, the average age being about 33 days. The results show that the same ratio of cement to aggregate, but with different sizes of stone, may furnish entirely different balancing of the mixture, and may thus affect directly the ultimate crushing strength.

Table VII. shows the ultimate crushing resistance of 2-inch

cubes made of various brands of neat cement tested at various ages. Each value is a mean of from five to six specimens, all of which set and hardened in the air.

The following series of compression tests (Table VIII.) on cement and mortar bricks, 9 inches x 4½ inches x 3 inches, is recorded by John Grant in the Proceedings of the Institution of Civil Engineers, Vol. XXXII., page 288. Ten specimens were prepared from each mixture, the composition being as shown in the table; five were allowed to harden in air and five in water, the age when tested being one year. The results as published are expressed in tons, and in reducing the figures it was assumed

TABLE VII.

Age in Days	Ultimate Compressive Strength in Lbs. per Sq. In.					
	Storm King Portland	Alsen Portland	Lehigh Portland	Hoffman Rosendale	Norton Rosendale	Potomac Rosendale
1....	577	1140	——	261	225	145
7....	1400	3980	4540	543	476	403
14....	1820	3830	5210	676	609	590
30....	2160	4170	5760	1010	878	1010

TABLE VIII.

Mixture	Crushing Resistance in Lbs. per Sq. In.	
	Left in—	
Cement : Sand	Air	Water
Neat....................	5370	7350
1:1....................	4580	4620
1:2....................	3880	3170
1:3....................	2980	1470
1:4....................	2420	1160
1:5....................	2070	835
1:6....................	1680	622
1:7....................	1600	584
1:8....................	1070	453
1:9....................	970	412
1:10....................	855	312

that the ton of 2,240 pounds was meant. The specimens were either rammed or pressed by hydraulic press at the time of making.

Grant also made a series of tests (Table IX.) on concrete blocks, some of which set in air and were so kept for one year,

1:7	1160	1250	1030	990
1:8	950	1180	840	840
1:9	840	1060	750	680
1:10	760	745	625	625

those cubes in which the material was pressed or rammed in the moulds are here considered.

It appears that each figure is the average of two tests, but the

TABLE X.

Brand of Cement	Composition			Age		Ult. Resist. in Lbs. per Sq. In.
	Cement	Sand	Broken Stone	Years	Months	
Alpha Portland	1	2*	——	1	—	4906
" "	1	2	4—⅝ In. Trap	1	—	3187
" "	1	3	6 " "	1	—	2070
" "	1	4	8 " "	1	—	1499
" "	1	5	10 " "	1	—	949
" "	1	6	12 " "	1	—	791
" "	1	2	4 {1½ & 2½ In. Trap}	2	—	2789
" "	1	2	4 {1 & 2½ In. Trap}	2	—	2549
" "	1	2	4—2½ In. Trap	2	—	2466
" "	1	2	7 " "	1	2	2406
" "	1	2	4 {1½ to 3 In. Pebbles}	1	2	3589
" "	1	2	4 {1½ to 2½ In. Brok'n Brick}	1	2	3241
" "	1	3	6 "	1	1	2545
" "	1	4	——	1	1	1446

*Granite dust.

composition of the concrete is not clearly explained; the aggregate is called ballast and sand. The tables are inserted on ac-

count of the interest attached to them, for the experiments were made in 1867.

Table X. is taken from the Watertown Arsenal Report for the

TABLE XI.

Parts by Weight of Sand to Cement	Ultimate Crushing Resistance per Sq. In.
1:1	11330
1:1½	10390
1:2	9520
1:2½	8110
1:3	6140
1:3½	6280
1:4	5230

year 1901, and shows the ultimate crushing resistance of 12 inch cubes, composed of various proportions of cement, sand and broken stone.

TABLE XII.

Brand of Cement	Percentage of Water	Compressive Strength in Lbs. per Sq. In. at an Age of—		
		7 Days	1 Month	3 Months
Alpha Portland	25	6010	7340	8580
Atlas "	25	3490	5370	5870
Lehigh "	26.8	4280	5590	6310
" "	18	5780	5990	6980
Star Portland	22½	4620	5180	5930
" "	25	5560	5980	7730
" "	30	5030	5620	6810
Whitehall Portland	25	5630	6640	7630
Alsen "	29.2	3510	4940	5510
Josson "	26.7	2750	4030	4660
Cathedral "	26.7	2110	2970	3430
" "	18	3860	3970	4490
Silica Cement	28½	1300	1790	2110
" "	18	3050	3470	4470
Austin Natural	35.4	356	1090	1530
Bonneville Improved Natural	38.7	620	1130	1560
Hoffman Natural	36.2	464	790	1230
Mankato "	41.2	566	1020	1420
Newark & Rosendale Natural	38.7	407	1090	1440
Norton Natural	39.6	472	880	1570
Obelisk "	35.8	750	1360	2220
Potomac "	39.2	423	840	1110

Table XI. gives the values of the compressive resistance of cement mortar cubes; the tests were made for the United States Engineering Corps and are recorded in the Watertown Arsenal

accounts for this. Table XII., which is taken from the same report, shows the ultimate crushing strength of four-inch cubes of neat cement with various brands of Portland and natural cements. Each result is a mean of from four to five speci-

TABLE XIII.

	Ultimate Crushing Strength in Lbs. per Sq. In.	
	With Fine Sand	With Coarse, Sharp Sand
Standard Limestone..................	1595	1825
Selected Stone, Containing Some Mica..	1185	2145
Stone Rejected for Use................	985	1102

mens. All the specimens set in air. In not one of these tests did the ultimate crushing resistance approach that shown in Table XI.

Table XIII. gives the crushing strength of concrete composed of one part Portland cement, three parts sand and five parts stone, in eight-inch cubes, as reported by T. S. Clark in Engineering News of July 24, 1902. The table is given for the purpose of showing that different crushing strengths may be attained by concrete with different classes of stone. The cubes were kept in air twenty-four hours and in water five months before being tested. The three kinds of stone used were standard limestone, a stone containing a large amount of mica and which had been rejected for use, and a better quality of this rejected stone containing less mica. It will be seen that the quality of both the sand and the stone bears intimate relation to the final crushing

strength, and the rather vague opinion that a calcareous stone is better than other kinds is to a certain extent corroborated.

Setting Under Water—Table XIV. is taken from the Report of the Watertown Arsenal for 1902, and furnishes comparative crushing tests on mortars which were allowed to set both in air and in water. The majority of the specimens were two-inch cubes; larger size cubes are noted. The specimens which were placed in water were allowed to set first one day in air, and each result is an average of from four to five specimens. It will be seen that almost uniformly those specimens which set under water attained the greater compressive strength. The table only shows results for one brand of cement, but in all seven brands

TABLE XIV.

Brand of Cement	Composition			Age in Days		Compressive Strength in Lbs. per Sq. In.	Remarks
	Cement	Sand	Water Per Ct.	Air	Water		
Atlas.........	1	1	32.0	7	—	2540	
"	1	1	32.0	1	6	2580	
"	1	1	32.0	30	—	3010	
"	1	1	32.0	1	29	3470	
"	1	1	32.0	92	—	3390	
"	1	1	32.0	1	91	4550	
"	1	1	32.0	93	—	4100	3 In. Cubes (Each result is a mean of 2 specimens)
"	1	1	32.0	1	92	6590	3 In. Cubes
"	1	1	33.7	92	—	3555	4 In. Cubes
"	1	1	33.7	1	91	5000	4 In. Cubes
"	1	1	33.7	92	—	3805	6 In. Cubes
"	1	1	33.7	1	91	5630	6 In. Cubes
"	1	1	32.0	183	—	3370	
"	1	1	32.0	1	182	4800	

were tested, for neat, 1:1 and 1:3 mixtures. All the tests furnish similar results.

These results do not corroborate those of Grant, previously recorded, in which the specimens under water were almost invariably weaker. Table XIV., taken in connection with Mr. Rafter's tests, indicates, however, that mortars and concretes kept damp or under water are in general the stronger. The latter is the author's opinion.

Wet or Dry Concretes—Table XV. shows results obtained from experiments made as thesis work by J. W. Sussex, published

	Tamped	Tamped	Tamped	Tamped	
7 Days	1200	1340	2280	1330	1040
1 Month	1750	1960	2290	2560	2230
3 Months	2500	2600	2150	2590	3040

volumes of sand containing a small percentage of fine gravel and six volumes of crushed limestone. Tests were made with the three degrees of plasticity noted, and also with two degrees of tamping—light and hard. Each result shown is an average of three tests. At the end of three months it will be seen that the wet concretes furnished the greatest ultimate resistance, although

TABLE XVI.

Kind of Cement and Sand	Age in Days	Ultimate Compressive Resistance in Lbs. per Sq. In. When Mixed		
		Dry	Medium	Wet
Portland; Bar Sand	7	1330	1230	1245
" White "	7	1650	1500	1450
Natural; Bar "	7	258	292	328
" White "	7	427	253	138
Portland; Bar "	28	2560	1890	1320
" White "	28	2360	2470	1540
Natural; Bar "	28	481	507	334
" White "	28	708	470	282

at the end of seven days and one month the medium specimens furnished the highest ultimate resistance, whether tamped lightly or hard.

T. L. Doyle and E. R. Justice record in "Engineering News" for July 30, 1903, the ultimate compressive resistances of six-inch cubes made with both Alpha Portland and Hoffman natural ce-

ments and mixed to three different consistencies. Two kinds of sand, white sand and bar sand, were used, and the stone was one-inch trap rock. The ages of the specimens were seven and twenty-eight days. Table XVI. shows the results obtained, each figure being an average of five tests. It will be seen that in all cases the dry specimens furnished higher ultimate resistances than either of the other two kinds. The age of the specimens is not sufficient to show whether the wet mixtures would not ultimately be stronger than the dry.

High Temperatures—The effect of high temperatures on cement mixtures has not been studied to any extent as yet, but Table XVII., which is taken from the Watertown Arsenal Report for 1902, shows the variation in the ultimate crushing strength of four-inch cubes after they had been heated to different temperatures. The age of the cubes was, in most cases,

TABLE XVII.

Composition		Ultimate Crushing Strength in Lbs. per Sq. In. After Heating to								
Cement	Sand	Not Heated	200° F.	300° F.	400° F.	500° F.	600° F.	700° F.	800° F.	900° F.
1 Alpha*	—	9167	8830	7920	9190	9400	9333	8217	8060	6060
1 Alpha†	—	12480	14447	13853	13767	13910	12787	12130	9985	—
1 Dyckerhoff*	—	5017	—	—	—	—	4313	3483	4280	—
1 Mankato*	—	1867	1657	1876	1966	1603	1453	1496	1400	1185
1 " †	—	3873	4043	3523	3810	4133	4013	3957	3900	2990
1 " *	1	538	491	432	—	471	—	381	—	317
1 " †	1	2170	2067	1953	—	2063	—	2240	—	1767

*Cubes set in air before heating. †Cubes set in water before heating.

slightly over one year, and they were tested, usually, about thirty days after having been heated. Each result is an average of three tests. It will be seen that there is practically no decrease in strength, even up to a temperature of 600 degrees Fahr., but a decrease is shown for higher temperatures.

Art. 23.—Compressive Properties.

Conclusions.

It has seemed to the author that the graphical method used in determining the straight-line formula for long columns was the most rational way to combine the experiments which have been recorded in the preceding pages. Two sets of straight-line dia-

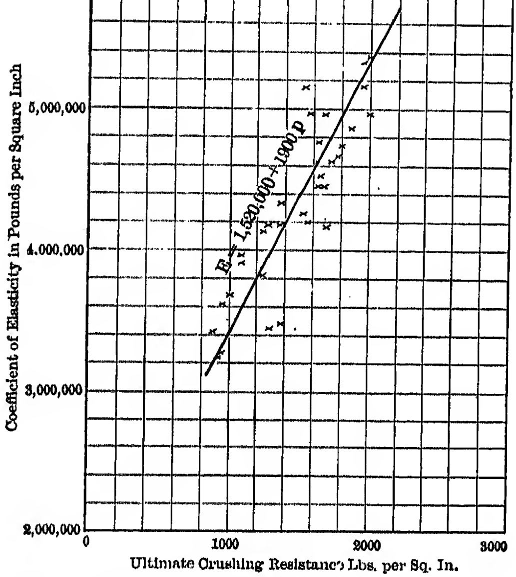


FIG. 1.—FROM BACH'S TESTS.—TABLE I., ART. 21.

need but little explanation; each represents graphically one of the tables which have been recorded in the previous pages. Tables III., IV., V. and VI. of Art. 21 have not been included, since the values there shown are not the true or elastic coefficients; Table VII. has not been included on account of the limited number of tests.

There has also been included in Figure 8 a summary of the tests made at the Watertown Arsenal in 1899 on twelve-inch concrete cubes varying in age from one to six months. The tests

were made with five well known brands of Portland cement, with various mixtures of sand and stone.

The tests made by Messrs. Derleth and Hawkesworth were not sufficient in number to enable their results to be included in a figure.

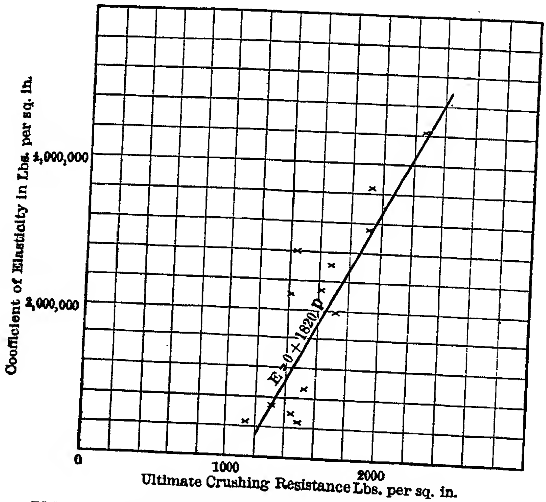


FIG. 2.—FROM BACH'S TESTS.—TABLE II., ART. 21.

Figures 1 to 9 represent the variation of the coefficient of elasticity with the variation of the ultimate compressive resistance. The equations of the lines there shown are as follows, p representing the ultimate compressive resistance:

$E=1,520,000+1900p$	(Bach)	Fig. 1.
$E=\quad 0 \quad +1820p$	(Bach)	Fig. 2.
$E=\quad 0 \quad +1000p$		Fig. 3.
$E=\quad 0 \quad +1090p$		Fig. 4.
$E=\quad 0 \quad +1600p$	(Hatt)	Fig. 5.
$E=\quad 0 \quad +1570p$	(Austrian)	Fig. 6.
$E=\ 62,000+\ 794p$	(Rafter)	Fig. 7.
$E=\quad 0 \quad +1150p$		Fig. 8.
$E=\quad 0 \quad +1000p$	(McCaustland)	Fig. 9.

lowing:

$$E = 1325p.$$

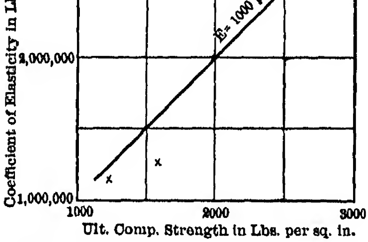


FIG. 3.—EASTERN EXPANDED METAL CO.'S TESTS.—FROM TABLE VII., ART. 21.

The constant 175,000 may be neglected with all the more safety since it depends mainly on one series of experiments, viz., Professor Bach's, and in these experiments the coefficients are undoubtedly higher than in other cases, on account of the repeated application of every load.

In a similar way, Figures 10 to 15 represent the variation of the ultimate crushing resistance with the variation in the ratio of the cement to aggregate; the following equations are then obtained:

$p = 4750 - 250m$ .... (Bach) Fig. 10.
$p = 5140 - 238m$ .... (Rafter) Fig. 11.
$p = 4578 - 289m$ .... (Rafter) Fig. 12.
$p = 3835 - 207m$ .. (Watertown, Table V.) Fig. 13.
$p = 3440 - 280m$ .... (McCaustland) Fig. 14.
$p = 5035 - 214m$ ...... (Watertown, 1899) Fig. 15.

Henby's tests (page 112) in addition furnish an equation of

$$p = 4350 - 258m.$$

The average of all these equations furnishes

$$p = 4449 - 247m,$$

in which p equals the ultimate crushing resistance and m the

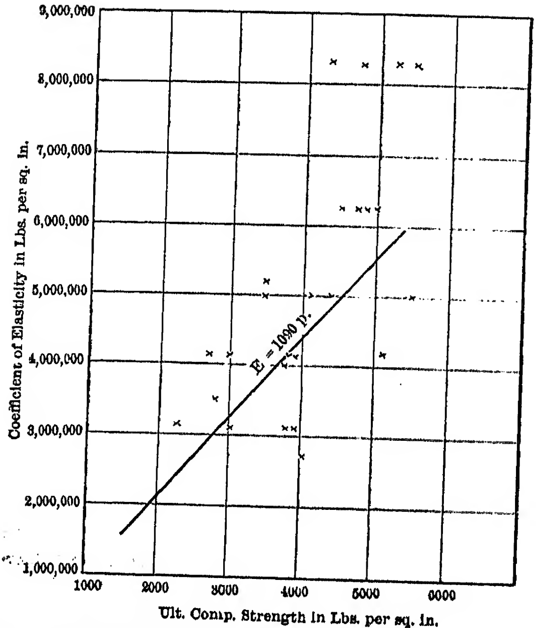


FIG. 4.—WATERTOWN, 1898, TESTS.—TABLE VIII., ART. 21.

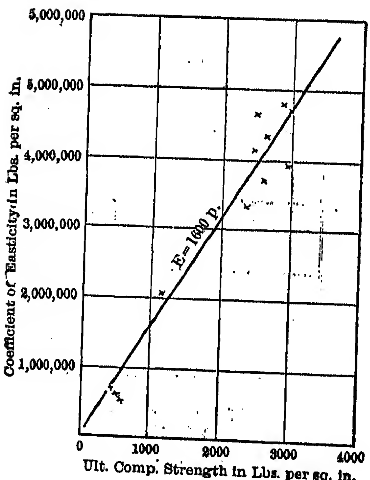


FIG. 5.
HATT'S TESTS.—TABLES VI. AND VII., PAGES 83 AND 84.

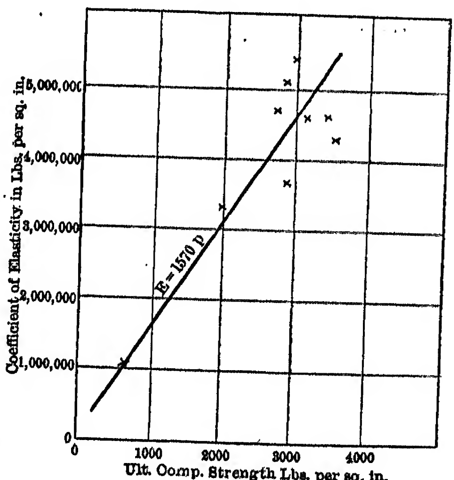


FIG. 6.
AUSTRIAN SOCIETY'S TESTS.—TABLE IX., PAGE 96.

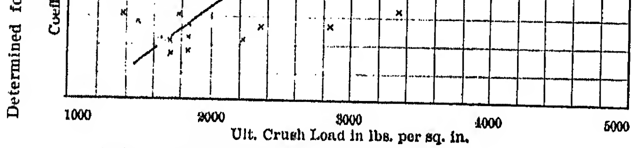


FIG. 7.—RAFTER'S TESTS.—TABLE IX., ART. 21.

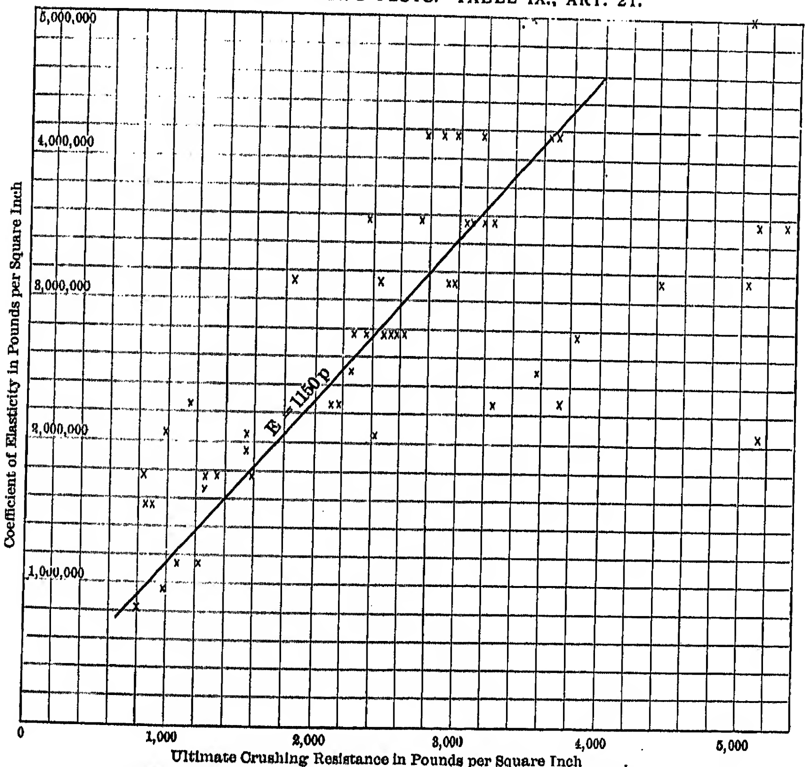


FIG. 8.—WATERTOWN, 1899, TESTS OF FIVE WELL-KNOWN BRANDS OF PORTLAND CEMENT.

ratio of aggregate to cement. This equation may be used with safety to determine the strength of any mixture, with m between the limits of 4 and 16.

The question of the ultimate strength of cement mixtures has been considered by the author from one point of view only, viz.,

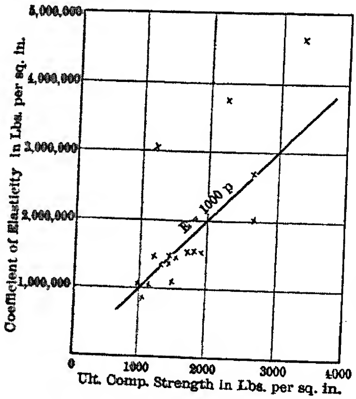


FIG. 9.
McCAUSTLAND'S TESTS.
FROM TABLE X., ART. 21.

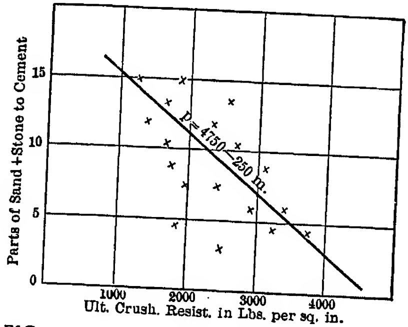


FIG. 10.—BACH'S 1896 TESTS, ON 10-IN. CYLINDERS, 10 INS. HIGH. TABLE II., ART. 21.

the relation between the cement to the aggregate. Another method of dealing with this question has, however, been studied by R. Feret in Europe, and is being studied by William B. Fuller in America; the latter's results are not yet published. This

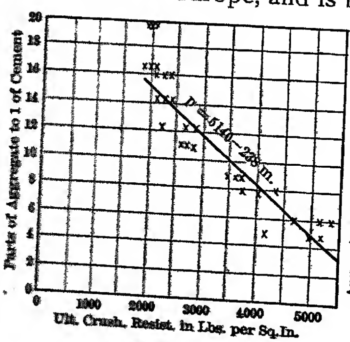


FIG. 11.
RAFTER'S TESTS.
FROM TABLE I., ART. 22.

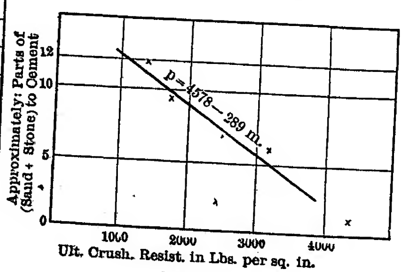


FIG. 12.
RAFTER'S TESTS.
FROM TABLE IV., ART. 22.

method considers not merely the relation between the cement and the aggregate, but also the balancing of the entire mixture.

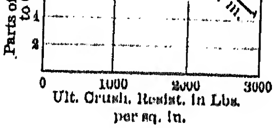


FIG. 13.
WATERTOWN TESTS.
FROM TABLE V., ART. 22.

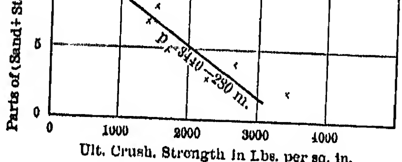


FIG 14.—McCAUSTLAND'S TESTS.
FROM TABLE X., ART. 21.

of sand. This variation in strength is in proportion to the variation of the solid material in the mass, the maximum value being obtained when the medium sized grains are eliminated. This was found to hold true no matter under what conditions the mor-

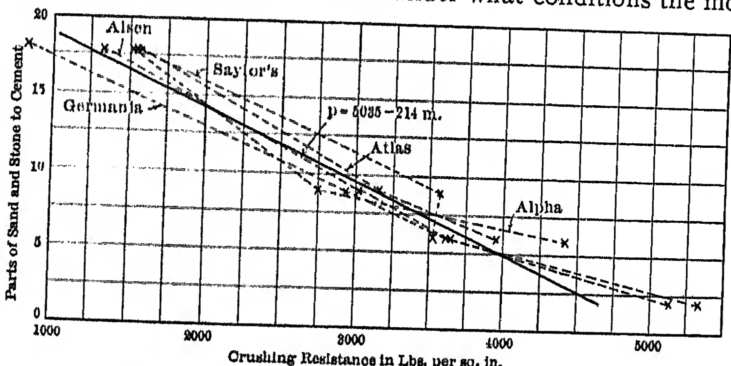


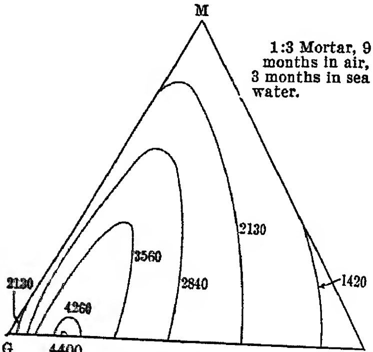
FIG. 15.—WATERTOWN, 1899, TESTS ON FIVE WELL-KNOWN BRANDS OF PORTLAND CEMENTS.

tars were allowed to set and harden. Feret cites numerous examples, but Figures 16 and 17 are characteristic of all his experiments. In this case the percentages of the various sizes of sand grains are represented on the perpendiculars erected on the sides

of an equilateral triangle, a system of co-ordination which is familiar. The ultimate crushing resistance of the various mortars is marked at the proper points within the triangle; with these points as guides, contour lines, representing mixtures having an equal ultimate resistance, are then drawn.

Figure 16 shows very clearly how the strength of the mixture increases as the medium sized grains are eliminated.

Figure 17 was drawn in a similar manner, but represents the relation of solid matter to the total cubic contents in a freshly mixed mortar. The close similarity between these two figures



Note: The letters G, M, F, indicate large, medium and fine grains of sand.

FIG. 16.

Showing the Ultimate Compressive Resistances, in Lbs. per Sq. In., of Mortars, Mixed with Differing Percentages of Various Sized Sand.

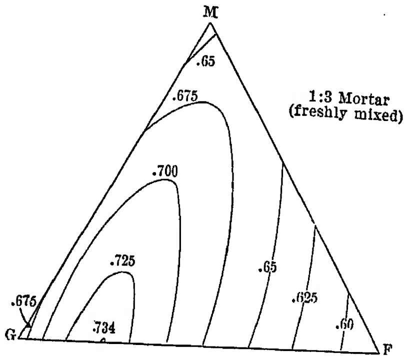


FIG. 17.

Showing Proportion of Solid Matter to Total Cubic Contents of Mortars Mixed with Differing Percentages of Various Sized Sand.

is noticeable and checks Feret's conclusion that the ultimate compressive resistance varies in proportion to the solid matter in a specimen. It will require much work of this character in order that some definite conclusions may be obtained.

Considering in general all the tests which have been tabulated, it may be concluded:

First—That concretes in compression have a point that may be termed the elastic limit, and its value is between one-half and two-thirds of the ultimate resistance.

Second—That up to this elastic limit the compressive coefficient of elasticity may have in general a value of 1325 times the ultimate crushing resistance.

oncretes.

fth—That concretes hardening under water attain slightly ter ultimate resistance than the same mixtures hardening in

xth—That temperatures below 600 degrees Fahr. do not af- adversely the strength of concretes.

has been shown that there is no appreciable increase in gth after the material is three months old. Therefore, if it sired that a concrete should possess ultimately a high value ie coefficient of elasticity, it is possible to obtain it only by g richer mixtures.

nd, finally, it appears that the values of the coefficients of icity for tension and compression are practically equal.

CHAPTER VII.

FLEXURAL PROPERTIES.

Art. 24.—The Theory of Flexure as Applied to Concrete.

Careful consideration must be given to the theory of flexure in connection with concrete beams in flexure. In determining the coefficient of elasticity for flexure two conditions in the theory of flexure are usually assumed, viz., that the coefficients of elasticity for direct tension and direct compression are equal, and that they are constant. This is rarely, if ever, the case; but in order to determine the deflections of beams it is necessary to make these assumptions in order to determine the empirical value for the flexural coefficient of elasticity. It has been shown that neither of these assumptions holds *precisely* for concrete, and that, therefore,

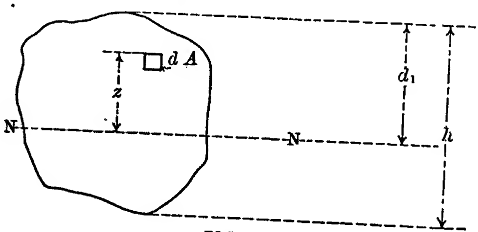


FIG. 1.

the value of the coefficient of elasticity which may be deduced for bending has no reasonable basis; but it seems to be perfectly proper to determine it as an empirical quantity, since it is a possible way in which to determine in advance the deflection of these concrete beams.

The quantity, which is usually called the modulus of rupture, or the extreme fibre stress at rupture, is probably as correct a quantity for concrete as in the case of any other material, even such as steel or wrought iron. This modulus of rupture is de-

the deflection of a beam composed of a material having unequal coefficients of elasticity for tension and compression is of considerable interest on account of the simplicity of the final equations. Let Figure 1 represent the cross section of a beam of such a material, NN representing the neutral axis as determined in some possible way.

The following notation will be used:

p=intensity of stress at units distance from NN;
z=the distance of any elementary area dA, from NN;
u=the unit strain corresponding to p;
E_t and E_c=the coefficients of elasticity of the materials for tension and compression respectively;
A_t and A_c=the areas at any section which carry tension and compression respectively;
I_t and I_c=the moments of inertia of A_t and A_c respectively about NN as an axis.

From the general theory of flexure, the moment of the stress acting on the differential area dA, distant z from NN, about that axis is:

$$z \,.\, p \,.\, dA \,.\, z = E\mu \,.\, z^2 .\, dA.$$

The differential internal moment, integrated over the entire section, becomes equal to M, the external moment:

$$M = E_c\,\mu \int_0^{d_1} z^2 .\, dA_c + E_t \,.\, \mu \int_0^{h_1-d_1} z^2 .\, dA_t \quad . \quad . \quad . \quad (1)$$

$$= E_c \,.\, I_c \,.\, \mu + E_t \,.\, I_t \,.\, \mu \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

* *Trans. Am. Soc. C. E., Dec., 1903.*

But $\mu = \frac{I}{\rho} = \frac{d^2\omega}{dx^2}$, if ρ represents the radius of curvature of the neutral axis; therefore

$$M = E_c \cdot I_c \cdot \frac{d^2\omega}{dx^2} + E_t \cdot I_t \cdot \frac{d^2\omega}{dx^2}$$

$$\text{or, } \frac{d^2\omega}{dx^2} = \frac{M}{E_c I_c + E_t I_t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If $E_c = E_t$, then $\frac{d^2\omega}{dx^2} = \frac{M}{EI}$ where I represents the moment of inertia of the entire section about NN.

By the aid of Eq. 3, it would be possible to determine both E_t and E_c, by means of the deflections found under two different loads, provided the position of the neutral axis could be determined. To determine the neutral axis it becomes necessary to know in advance, or to assume, both E_t and E_c. If assumed, the correctness of these values must then afterward be checked by means of the deflections.

To pass through such a procedure becomes a tedious task, more especially, as has been shown, that E_t and E_c for concrete do not differ greatly, if at all. In all his work the author therefore has calculated the apparent flexural coefficient of elasticity, assuming E_t equal to E_c.

Since concrete beams show permanent deflections under comparatively light loads, it also becomes necessary, as in the case of pure compression, to distinguish between the *elastic* coefficient and one calculated from the total strains only.

Art. 25.—Flexural Coefficient of Elasticity.

Table I. and Figure 1 are taken from a paper by the author and recorded in the Transactions of the American Society of Civil Engineers, 1903. The table shows the values of the flexural coefficient of elasticity and of the extreme fibre stress for concrete beams 4x4 inches x36 inches span, tested to destruction by a centre load. The table is of interest on account of the age of the specimens tested, which was seven and one-third years. The mixtures used are given in the table; the sand was Cow Bay, L. I.,

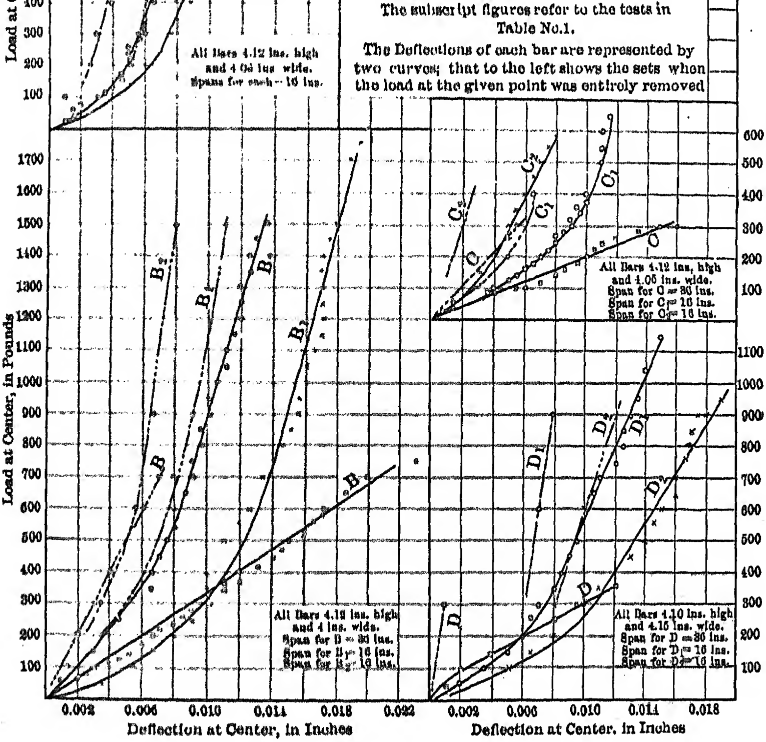


FIG. 1.

curves lettered with the same subscript. The curve to the left shows the set when the load at that given point was entirely removed. It was found that the true or elastic coefficients of elas-

ticity, calculated in the way which has already been explained, gave constant values for the coefficient for any one specimen almost up to the breaking load. The table shows that neither the coefficient nor the ultimate strength shows any remarkable increase for very old specimens. They may increase for beams less than one year old, but for bars of the age shown in the table neither of the constants shows any material increase.

TABLE I.

Bar	Age in Years	Span in Inches	Section of Bar in Inches		Coefficient of Elasticity in Lbs. per Sq. In.	Extreme Fibre Stress in Lbs. per Sq. In.
			Depth	Width		
A.....	7.4	36	4.12	4.06	——	——
A_1....	7.4	16	4.12	4.06	1,591,000	278
A_2....	7.4	16	4.12	4.06	1,102,000	315
B.....	7	36	4.12	4.00	2,122,000	606
B_1....	7	16	4.12	4.00	2,440,000	636
B_2....	7	16	4.12	4.00	1,220,000	530
C	7	36	4.12	4.05	1,315,000	247
C_1....	7	16	4.12	4.05	387,000	229
C_2....	7	16	4.12	4.05	1,023,000	208
D	7.3	36	4.10	4.15	1,165,000	294
D_1....	7.3	16	4.10	4.15	597,000	415
D_2....	7.3	16	4.10	4.15	597,000	346

Bars A=1 Aalborg cement, 2 sand and 4 gravel.
" B=1 Atlas cement and 3 sand.
" C=1 Alsen cement, 3 sand and 5 gravel.
" D=1 Alsen cement and 2 sand.

In discussing these experiments Professor E. J. McCaustland records in the same Transactions some experiments made by him on neat cement beams 2x2¾ inches deep x24 inches span, one year old, tested by centre loads.

TABLE II.

Specimen No.	Brand	Coefficient of Elasticity in Lbs. per Sq. In.	Extreme Fibre Stress in Lbs. per Sq. In.
1	Cayuga Lake......	——	571
2	" "	1,384,000	357
3	" "	600,000	238
4	" "	460,000	190
5	Empire Portland...	1,219,000	623
6	" " ...	1,582,000	618
7	" " ...	920,000	452

Table II. shows results of the constants determined in the same

flexure, which is not a part of the present discussion.

For the plain concrete beam, whose age was forty days, the value of the extreme fibre stress was found to be 170 pounds per square inch, the composition of the concrete being one part Portland cement, three parts sand, four parts of trap rock passing a one-inch ring sieve, and two parts of the same rock passing a ½-inch ring sieve, all proportions being measured by volume.

Jules A. Coelos and R. A. W. Carleton, graduating students of the Civil Engineering course at Columbia University, 1904, performed during the winter of 1903-04 an extended series of tests on plain and reinforced concrete beams 6x6 inches in cross section, tested on a span of 36 inches. The materials which were used were exactly the same as those used in the direct tension and compression tests recorded previously on page 84 in the experiments of Messrs. Derleth and Hawkesworth, and need no further explanation.

The loading was either a single centre loading or was placed at two points symmetrically distant from the centre of the span. The deflections were read in the centre of the beam in the same manner as the tests which were recorded in Table I., and the coefficient of elasticity was calculated as the true coefficient.

Only the plain concrete beams are given in Table III. Tests of the ultimate shearing resistance of the bars were made after they had been broken, and these values are also given in the table.

W. L. Brown has recorded in the Proceedings of the Institution of Civil Engineers, 1898-1899, a series of tests on cross

bending of neat cement and mortar mixtures. The size of the specimens was always 2 inches deep by 1 inch wide by 30 inches span. Three kinds of sand were used—a good ordinary coarse red sand, well washed; a poor argillaceous fine sand, unwashed, and a fine Laxey gravel, which was really a very coarse sand.

Two sets of experiments were made, using two brands of cement. The deflections were measured at the centre of the beams, the loads being placed at the same points. The coefficients of elasticity were determined from the formula of the common theory of flexure and calculated between the extreme limits of stress obtained. The breaking load varied from a centre load of 5 to 35

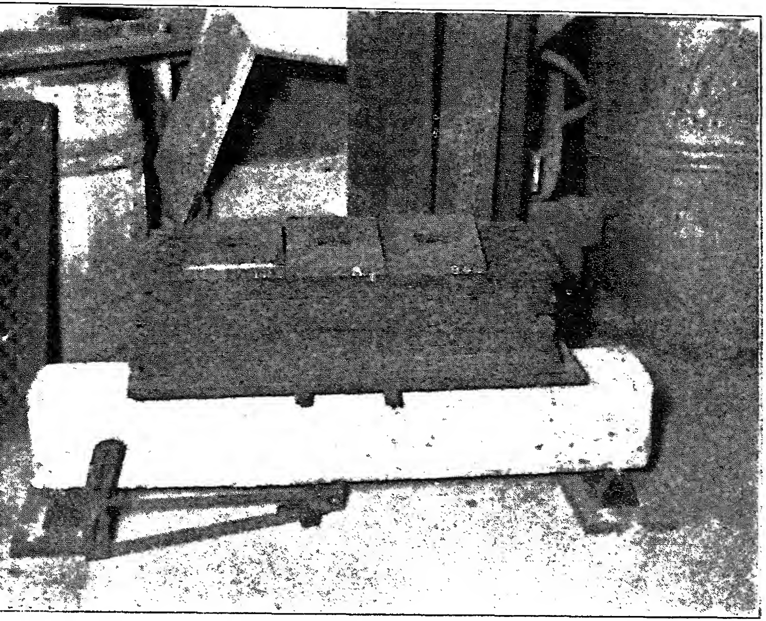
TABLE III.—FLEXURAL TESTS ON 1:3:5 PORTLAND CEMENT CONCRETE BEAMS, 6x6x36 INCH SPAN.

No.	Age in Days	Loading	Coefficient of Elasticity in Lbs. per Sq. In.	Net Fibre Stress Lbs. per Sq. In.	Shearing Tests Shearing Intensity in Lbs. per Sq. In.	
					At First Crack	At Failure
1.......	127	At 2 Points	1,118,900	170	180	256 196
2.......	128	" "	1,002,300	218	118 153	178 180
5.......	128	" "	1,440,900	189	101	168 255
7.......	125	" "	2,161,500	225	167	214
8.......	141	At Centre	1,012,500	148	97 86	——
21.......	121	"	1,205,500	223	—	330 226

pounds. On account of the small sizes of the specimens and on account of some ambiguity in the methods of calculation, it has been thought better not to give here in detail the experiments themselves, but merely Mr. Brown's general conclusions:

That E is greater for neat cements than for mortars; that E varies inversely with the amount of sand in a specimen; that the quality of sand affects E, but not considerably, but that age does increase E to a measurable extent.

Some experiments on the coefficient of elasticity of concrete beams have been recorded by Durand-Claye in "Annales des Ponts et Chaussées," 1888, and are here shown in Table IV. Tests were made on seven bars; six were neat Portland cement



of Testing Specimens Nos. 1, 2, 5 and 7 Stone Concrete of Table III. Loads Applied at Two Points at Equal Distances from the Centre of Span.

Composition in Parts by Weight		Age When Tested	How Kept	Coefficient of Elasticity in Lbs. per Sq. In.	Extreme Fibre Stress in Lbs. per Sq. In.	Net Tensile Resistance of Similar Specimens in Lbs. per Sq. In.
Cement	Sand					
Neat	——	5 to 6 Weeks	Under Water	3,380,000	1000	880
"	——	" "	" "	3,370,000	950	823
"	——	" "	" "	2,810,000	781	667
"	——	" "	" "	3,410,000	1020	824
"	——	" "	" "	3,340,000	923	780
"	——	6 Months	In Air	3,860,000	1090	950
1	2	2 "	——	3,410,000	370	270

pure tension or compression; its value does not appear to differ greatly from that found in those cases.

Art. 26.—Modulus of Rupture in Bending.

Table I. gives the results of flexural tests on 111 concrete beams, as reported by E. S. Wheeler in the Report of the Chief of Engineers, U. S. Army, for 1895, p. 2922. The specimens were all 10 inches square and 4½ feet long, broken on a 4-foot span, with a centre load. In general the bars were kept covered with moist earth, awaiting the time of breaking. The age of the beams was between six months and two years. It will be seen that there is considerable difference in the strength of those beams when the stone used was sandstone or limestone. In almost every case the limestone furnished higher values of the modulus of rupture. The tests included beams mixed with both Portland and natural cements. Figs. 1 and 2 are plotted from the table, the ordinates being the extreme fibre stresses of the beams and the abscissæ being the ratios by volume of the aggregate (the sand and stone) to the cement. No attention was paid in

the figures to the difference in age of the various specimens, but tests Nos. 98 to 111 were not plotted. A straight line was drawn

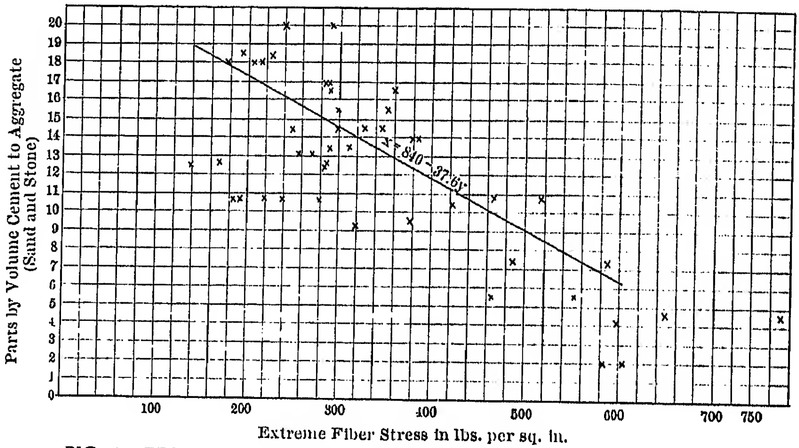


FIG. 1.—TESTS ON PORTLAND CEMENT BEAMS BY E. S. WHEELER.

to average as nearly as possible the results as plotted; the equation of the lines for Portland cement mixtures was found to be:

$$x = 840 - 37.6y$$

and for natural cements

$$x = 526 - 42.6y.$$

Using these lines as a basis, it will be seen that the greatest possible modulus of rupture which can be obtained is for the neat

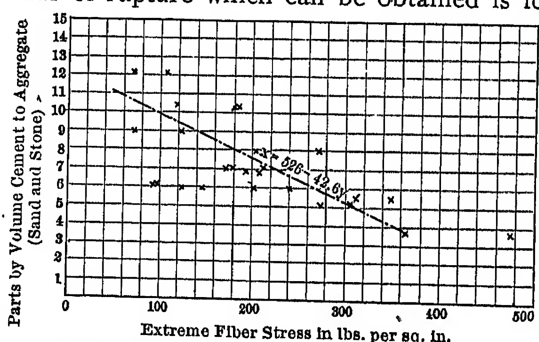


FIG. 2.—TESTS ON NATURAL CEMENT BEAMS BY E. S. WHEELER.

cement, and is respectively 840 and 526 lbs. per square inch for the Portland and natural. These values decrease steadily as the

32	"	3.14	7.61	[illegible] Gravel	"	144	219
33	"	3.14	7.61	Limestone and Gravel	"	151	239
34	"	3.14	7.61	Gravel	"	150	192
35	"	3.12	9.52	Limestone and Gravel	"	143	185
36	"	3.12	9.52	Gravel	"	139	139
37	"	3.07	9.52	Limestone	"	141	169
38	"	3.08	7.61	"	"	144	283
39	"	3.08	6.34	"	"	148	422
40	"	3.07	9.52	"	"	148	374
41	"	3.08	7.61	"	"	143	285
42	"	3.18	11.42	"	"	139	279
43	"	3.18	6.34	"	"	145	247
44	"	3.18	11.42	Limestone with Screenings	"	140	319
45	1 Natural	2.30	8.23	Gravel	"	141	298
46	"	2.27	6.86	"	"	150	120
47	"	2.25	10.17	"	"	151	74
48	"	2.27	6.86	Sandstone	"	146	110
49	"	2.25	10.17	"	"	146	123
50	"	1.87	5.33	"	"	131	74
51	"	1.87	5.33	"	"	138	181
52	"	1.87	5.33	"	"	139	214
53	1 Portland	4.16	13.9	"	"	138	175
54	"	4.16	13.9	"	"	133	177
55	"	4.16	13.9	"	"	132	213
56	1 Natural	1.50	5.38	"	"	132	204
57	"	1.50	5.38	"	"	140	194
58	"	1.50	5.38	"	"	136	210
59	1 Portland	5.2	13.2	"	"	—	—
60	"	5.2	13.2	"	"	135	193
61	"	5.2	13.2	"	"	141	221
62	1 Natural	1.12	4.15	"	"	—	—
63	"	1.12	4.15	"	"	140	275
64	"	1.12	4.15	"	"	137	306
65	1 Portland	2.1	11.1	"	"	—	—
66	"	2.1	11.1	"	"	132	255
67	"	2.1	11.1	"	"	134	269
68	"	4.16	12.4	"	20 Months	—	357
69	"	4.16	12.4	"	"	—	288
70	"	3.12	12.4	"	"	—	297
71	"	3.12	12.4	"	"	—	351
72	"	2.08	12.4	"	"	—	326
73	"	2.08	12.4	"	"	—	345
74	"	1.04	12.4	"	"	—	310
75	"	1.04	12.4	"	"	—	288
76	"	0.00	2.09	"	19 Months	—	582
77	"	0.00	2.09	"	"	—	605
78	"	1.04	3.76	"	"	—	652
79	"	1.04	3.76	"	"	—	727
80	"	2.08	5.57	"	"	—	488
81	"	2.08	5.57	"	"	—	588
82	"	3.12	7.71	"	"	—	513
83	"	3.12	7.71	"	"	—	465
84	"	4.16	9.86	"	"	—	376
85	"	4.16	9.86	"	"	—	382

TABLE I.—*Continued.*

	Proportionate Parts by Volume			Kind of Stone	Age When Broken	Wt. per Cu. Ft. of Concrete When Broken	Extreme Fibre Stress in Lbs. per Sq. In.
	Cement	Sand	Gravel				
86	1 Portland	5.20	11.93	Sandstone	19 Months	—	285
87	"	5.20	11.93	"	"	—	283
88	"	6.24	13.80	"	"	—	288
89	"	6.24	13.80	"	"	—	237
90	1 Natural	0.75	3.05	"	"	—	363
91	"	0.75	3.05	"	"	—	477
92	"	1.50	4.06	"	"	—	313
93	"	1.50	4.06	"	"	—	351
94	"	2.25	5.90	"	"	—	206
95	"	2.25	5.90	"	"	—	274
96	"	3.00	7.40	"	"	—	187
97	"	3.00	7.40	"	"	—	185
98*	1 Portland	2.08	5.64	"	8 Months	131	68
99*	"	2.08	5.64	"	16 Months	—	159
100	"	2.08	5.64	"	"	—	202
101	"	2.08	5.64	"	8 Months	146	110
102†	"	2.08	5.64	"	16 Months	—	245
103†	"	2.08	5.64	"	8 Months	143	145
104‡	"	2.08	5.64	"	"	138	142
105‡	"	2.08	5.64	"	16 Months	—	227
106	"	2.08	5.64	"	8 Months	142	131
107	"	2.08	5.64	"	16 Months	—	223
108§	"	2.08	5.64	"	8 Months	144	242
109§	"	2.08	5.64	"	16 Months	—	351
110¶	"	2.08	5.64	"	8 Months	145	203
111¶	"	2.08	5.64	"	16 Months	—	273

Nos. 98-111 not plotted in Fig. 1. *Frost in stone. †Water 100 deg. Fahr. ‡Water 156 deg. Fahr. §Water contained 18.75% salt. ¶Water contained 12.5% salt.

sand and stone are increased, until they become zero for a mixture of 22.5 parts and 12.5 parts for the Portland and natural respectively. A straight-line formula of this kind furnishes a convenient analytical guide to show the variation in strength of different cement mixtures.

Table II. is taken from tests reported by Mr. H. Von Schon, in the Transactions of the American Society of Civil Engineers for December, 1899, and shows results of Portland cement concrete beams 6x6x18 inches span, tested to destruction by flexure. The average age of the specimens which set in air was about 60 days. The sand was St. Mary's River; the broken sandstone was native Potsdam and the broken boulder stone was granitic. The broken stone all passed through a 1½-inch ring and was retained on a 1-inch ring.

The table shows five different mixtures, varying in richness of cement from the "D" mixture down to the "A" mixture. It will be seen that the richer mixtures always gave the highest

mission for the years 1901, 1902 and 1903, and shows the ultimate

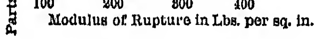


FIG. 3.

fibre stress of Portland cement concrete beams when tested to destruction. The specimens represented in the first six lines

TABLE II.—PORTLAND CEMENT CONCRETE BEAMS, 6x6x18-INCH SPAN.

Brand of Cement	Kind of Broken Stone	Mixture	No. of Tests	Ultimate Fibre Stress—Lbs. per Sq. In. Maximum	Mean	Minimum
E........	Sandstone	A	2	178	176	174
E.	"	B	2	225	217	209
E........	"	C	2	288	280	272
E........	"	D	2	329	325	321
E........	"	E	2	108	102	97
E........	Boulder Stone	A	2	354	326	298
E........	" "	B	2	358	328	299
E........	" "	C	2	390	373	356
E........	" "	D	2	420	410	400
E.	" "	E	2	350	330	310
R	Sandstone	A	2	181	169	158
R	"	B	2	183	175	167
R	"	C	2	266	262	258
R	"	D	2	328	308	288
R	"	E	2	195	182	169
R	Boulder Stone	A	2	390	347	204
R	" "	B	2	423	406	390
R	" "	C	2	410	392	374
R	" "	D	2	411	393	375
R	" "	E	2	332	322	312

Mixture A=1 cement, 2.4 sand, 5.3 broken stone.
Mixture B=1 cement, 2.4 sand, 4.8 broken stone.
Mixture C=1 cement, 2.4 sand, 4.4 broken stone.
Mixture D=1 cement, 2.4 sand, 4.0 broken stone.
Mixture E=1 cement, 0.3 lime, 3.1 sand, 5.3 broken stone.

were hand mixed; the next four were machine mixed; but the method of mixing the last two is not stated. The sand was

clean and sharp; the crushed stone was trap rock, 1 to $2\frac{1}{2}$ inches in size; and the stone dust was finely crushed stone, varying from

TABLE III.—PORTLAND CEMENT CONCRETE BEAMS, 6x6x30-INCH SPAN.

Composition by Volume					Age in Days	No. of Beams Broken	Ultimate Fibre Stress in Lbs. per Sq. In.			Remarks
Cement	Sand	Stone Dust	Gravel	Broken Stone			Max.	Mean	Min.	
1	1.2	—	1.8	—	30	4	640	525	442	Kept in ground.
1	1.2	—	—	1.8	30	7	634	571	341	Kept in ground; 26 in. span.
1	1.2	—	—	1.8	30	5	805	651	522	Kept in ground; 30 in. span.
1	1.2	—	—	1.8	136	3	1249	993	730	Kept in ground all winter.
1	1.2	—	—	1.8	30	14	913	689	444	———
1	—	1.2	—	1.8	30	33	1121	783	460	———
1	—	1.7	—	2.75	30	12	999	851	677	24 hours in compressed air at 7—12 lbs. per sq. in.
1	—	1.9	—	2.6	30	50	924	850	590	24 hours in compressed air at 12—18 lbs. per sq. in.
1	—	2.	—	2.4	30	30	904	731	622	48 hours in compressed air at 18—25 lbs. per sq. in.
1	—	2.	—	2.4	30	100	900	728	523	28—30 days in compressed air at 20—25 lbs. per sq. in.
1	2.5	—	—	4.	3 Yrs.	2	972	849	726	Buried in sand under sea water.
1	2.5	—	—	4.	"	1	———	809	———	Buried in fresh earth.

an impalpable powder to $\frac{1}{8}$ inch in diameter. It will be seen that the beams mixed with stone dust give higher results than those mixed with sand.

Table IV. is an abstract from the Report of the Boston Transit

TABLE IV.

No. of Beams Tested	Dimension.	Modulus of Rupture in Lbs. per Sq. In.			Average Days in Ground	Remarks
		Max'm	Mean	Minimum		Ingredients
4....	6x6x30 In.	640	525	442	28	Cement; Coarse, clean and sharp sand; Gravel.
7....	6x6x26 In.	634	571	341	28	Cement; Coarse, clean and sharp sand; Trap rock, 1 in. to $2\frac{1}{2}$ in.
5....	6x6x30 In.	805	651	522	28	
3....	"	1249	993	730	135	Cement; Coarse, clean and sharp sand; Trap rock, 1 in. to $2\frac{1}{2}$ in.
14....	"	913	683	444	28	Cement; Coarse, clean and sharp sand; Trap rock, 1 in. to $2\frac{1}{2}$ in.
33....	"	1121	777	460	28	Same as above, but stone dust instead of sand.

Commission for 1901, and records the results of tests made on concrete beams 6x6x about 30 inches in length. The propor-

1:3:7	176
1:4:9	146
1:6:11	112

pit and tested, when six months old. The stone used was screened pebbles, an inch or less in diameter. The modulus of rupture as calculated includes the weight of the beams.

Table VI. is taken from the Report of the Boston Transit Commission for the year ending June 30, 1902, and gives values of the ultimate fibre stress of concrete beams in flexure. The cement was Vulcanite Portland. The mixing was done by hand and the beams were kept the first twenty-four hours in air and

TABLE VI.—CONCRETE BEAMS 6x6x30 IN., 30 DAYS OLD.

Composition by Volume (Approx.)				No. of Tests	Size of Stone Dust	Ultimate Fibre Stress in Lbs. per Sq. In.		
Cement	Sand	Stone Dust	Broken Stone			Max.	Mean	Min.
1	—	2	2.4	4	Medium	947	848	760
1	.9	.9	2.7	4	"	846	784	704
1	1.6	—	3	4	"	773	711	656
1	.9	.9	2.7	4	Coarse	862	806	759

then twenty-nine days in damp earth. The results are of interest as showing the comparative strength of mixtures with stone dust and with sand. It will be seen that those beams in which the stone dust replaced the sand were the stronger and that in no case did the use of stone dust weaken the mixture.

Table VII. is taken from some tests reported by T. S. Clark, in Engineering News of July 24, 1902, and shows the relation

between the tensile strength of ordinary tensile briquettes and the extreme fibre stress of small concrete beams 1x1x8 inches. The same cement and aggregate were used for both kinds of tests and subjected to exactly the same treatment at the time of mixing. Each result shown is an average of from two to twelve specimens. All the mixtures were kept twenty-four hours in air, and the rest of the time presumably in water, although it is not so specifically stated. It will be seen that the ratio between the ultimate fibre stress in flexure as compared to the tensile strength varies from 1.32 to 1.66.

TABLE VII.

Composition of Specimen in Parts of				Age in Days	Ult. Tensile Strength in Lbs. per Sq. In.	Extreme Fibre Stress in Lbs. per Sq. In.	Ratio of Tension to Bending
Cement	Sand	Stone	Cinder				
Neat	—	—	—	30	809	1242	1.53
"	—	—	—	112	932	1406	1.50
1	2½	—	—	30	376	540	1.43
1	2½	—	—	60	482	634	1.32
1	2½	—	—	112	493	679	1.37
1	3	—	—	28	282	417	1.47
1	3	—	—	56	328	512	1.56
1	2	5*	—	28	187	304	1.63
1	2	—	5	30	110	183	1.66

*Beams 3x3x30 inches.

E. S. Wheeler records in the Report of the Chief of Engineers, U. S. Army, for 1896, p. 2870, an interesting series of tests, showing the relation between ultimate resistances of cement mixtures in tension, in bending and in compression; the compression tests will not be considered, however, since crude apparatus was employed.

The results from the tension and bending experiments are perhaps comparable, although the actual tension values obtained may be erroneous, on account of the use of the ordinary tensile briquette. This statement applies similarly to the preceding table. The transverse specimens were 2x2x8 inches, broken on a 5 1-3-inch span. The specimens for the two kinds of tests were always prepared from the same batch of mortar; each result in Table VIII. is an average of 4 to 10 breakings. It will be seen that the ratio of the extreme fibre resistance to the tensile

Cement	1 Day	7 Days	28 Ds.	3 Mos.	1 Year	1 Day	7 Days	28 Ds.	3 Mos.	1 Year
Neat	268	588	698	733	——	458	1115	1237	1340	——
1:1	——	484	630	705	721	——	607	915	1121	1185
1:2	——	294	——	491	——	——	407	——	764	——
1:3	——	182	277	338	379	——	247	397	541	582
1:5	——	——	——	187	252	——	——	——	286	369

ratios obtained in Tables VII. and VIII.; in conclusion it may therefore be said that the value of the modulus is about 1½ times the ultimate tensile resistance of the same material when tested in the standard briquette form. It seems doubtful if anything more exact can at the present time be determined.

Art. 27.—Transverse Shearing Resistance and Conclusion.

The resistance of cement mixtures to shearing stresses has not been treated separately on account of the lack of experimental data. On page 27 are given the results of some tests by Bauschinger, and on page 95 some results obtained at Columbia University. It is only possible to state that the value of the ultimate shearing resistance varies between the extreme limits of 125 to 375 pounds per square inch. The question of shear is of the greatest importance, and accurate and detailed experiments of the trasverse shearing resistance of concrete would be of great value.

The elastic properties of reinforced concrete beams have not been discussed in this work, except in connection with results having direct bearing on ordinary cement mixtures; principally because, in the opinion of the author, the elastic behavior of the combination may be deduced by analysis, with the aid of the

experimental values found separately for the two elemen
is his opinion that the combination of the two materials a
practice as rational theory might require, although some
lished experiments ascribe to concrete, when reinforced, dif
elastic properties than when not reinforced.

Presented at the Annual Meeting, January 21, 1903, and Amended at the Annual Meeting, January 20, 1904.

SAMPLING.

1.—*Selection of Sample.*—The selection of the sample for testing is a detail that must be left to the discretion of the engineer; the number and the quantity to be taken from each package will depend largely on the importance of the work, the number of tests to be made and the facilities for making them.

2.—The sample shall be a fair average of the contents of the package; it is recommended that, where conditions permit, one barrel in every ten be sampled.

3.—All samples should be passed through a sieve having twenty meshes per linear inch, in order to break up lumps and remove foreign material; this is also a very effective method for mixing them together in order to obtain an average. For determining the characteristics of a shipment of cement, the individual samples may be mixed and the average tested; where time will permit, however, it is recommended that they be tested separately.

4.—*Method of Sampling.*—Cement in barrels should be sampled through a hole made in the centre of one of the staves, midway between the heads, or in the head, by means of an auger or a sampling iron similar to that used by sugar inspectors. If in bags, it should be taken from surface to centre.

CHEMICAL ANALYSIS.

5.—*Significance.*—Chemical analysis may render valuable service in the detection of adulteration of cement with considerable amounts of inert material, such as slag or ground limestone. It is of use, also, in determining whether certain constituents, believed to be harmful when in excess of a certain percentage, as magnesia and sulphuric anhydride, are present in inadmissible proportions. While not recommending a definite limit for these impurities,

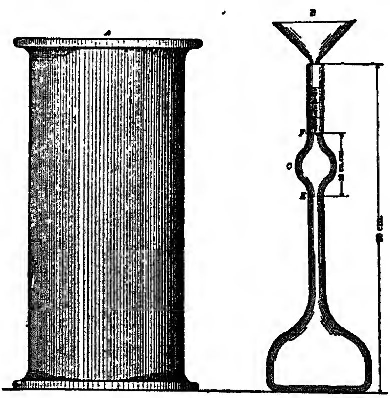
the Committee would suggest that the most recent and reliable evidence appears to indicate that magnesia to the amount of 5%, and sulphuric anhydride to the amount of 1.75%, may safely be considered harmless.

6.—The determination of the principal constituents of cement—silica, alumina, iron oxide and lime—is not conclusive as an indication of quality. Faulty character of cement results more frequently from imperfect preparation of the raw material or defective burning than from incorrect proportions of the constituents. Cement made from very finely ground material, and thoroughly burned, may contain much more lime than the amount usually present and still be perfectly sound. On the other hand, cements low in lime may, on account of careless preparation of the raw material, be of dangerous character. Further, the ash of the fuel used in burning may so greatly modify the composition of the product as largely to destroy the significance of the results of analysis.

7.—*Method.*—As a method to be followed for the analysis of cement, that proposed by the Committee on Uniformity in the Analysis of Materials for the Portland Cement Industry, of the New York Section of the Society for Chemical Industry, and published in the *Journal* of the Society for January 15th, 1902, is recommended.

SPECIFIC GRAVITY.

8.—*Significance.*—The specific gravity of cement is lowered by underburning, adulteration and hydration, but the adulteration must be in considerable quantity to affect the results appreciably.



Le Chatelier's Specific Gravity Apparatus.
FIG. 1.

9.—Inasmuch as the differences in specific gravity are usually very small, great care must be exercised in making the determination.

10.—When properly made, this test affords a quick check for underburning or adulteration.

11.—*Apparatus and Method.*—The determination of specific gravity is most conveniently made with Le Chatelier's apparatus. This consists of a flask (*D*), Fig. 1, of 120 cu. cm. (7.32 cu. ins.) capacity, the neck of which is about 20 cm. (7.87 ins.) long; in the middle of this neck is a bulb (*C*), above and below which are two marks (*F*) and (*E*); the volume between these marks is 20 cu. cm. (1.22 cu. ins.). The neck has a diameter of about 9 mm. (0.35 in.), and is graduated into tenths of cubic centimeters above the bulb.

12.—Benzine (62° Baumé naphtha), or kerosene free from water, should be used in making the determination.

13.—The specific gravity can be determined in two ways:

ically until the liquid starts to flow freely; it is then held still in a vertical osition until empty; the remaining traces of cement can be removed in a imilar manner by pouring into the flask a small quantity of clean liquid and epeating the operation.

18.—More accurate determinations may be made with the picnometer.

FINENESS.

19.—*Significance.*—It is generally accepted that the coarser particles in ement are practically inert, and it is only the extremely fine powder that ossesses adhesive or cementing qualities. The more finely cement is pul-erized, all other conditions being the same, the more sand it will carry and roduce a mortar of a given strength.

20.—The degree of final pulverization which the cement receives at the lace of manufacture is ascertained by measuring the residue retained on ertain sieves. Those known as the No. 100 and No. 200 sieves are recom-ended for this purpose.

21.—*Apparatus.*—The sieves should be circular, about 20 cm. (7.87 ins.) diameter, 6 cm. (2.36 ins.) high, and provided with a pan, 5 cm. (1.97 ins.) eep, and a cover.

22.—The wire cloth should be woven (not twilled) from brass wire having e following diameters:

No. 100, 0.0045 in.; No. 200, 0.0024 in.

23.—This cloth should be mounted on the frames without distortion; the esh should be regular in spacing and be within the following limits:

No. 100, 96 to 100 meshes to the linear inch.
No. 200, 188 to 200 " " " "

24.—Fifty grams (1.76 oz.) or 100 gr. (3.52 oz.) should be used for the test, and dried at a temperature of 100° Cent. (212° Fahr.) prior to sieving.

25.—*Method.*—The Committee, after careful investigation, has reached the conclusion that mechanical sieving is not as practicable or efficient as hand work, and, therefore, recommends the following method:

26.—The thoroughly dried and coarsely screened sample is weighed and placed on the No. 200 sieve, which, with pan and cover attached, is held in one hand in a slightly inclined position, and moved forward and backward, at the same time striking the side gently with the palm of the other hand, at the rate of about 200 strokes per minute. The operation is continued until not more than one-tenth of 1% passes through after one minute of continuous sieving. The residue is weighed, then placed on the No. 100 sieve and the operation repeated. The work may be expedited by placing in the sieve a small quantity of large shot. The results should be reported to the nearest tenth of 1 per cent

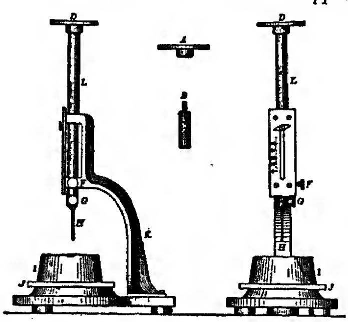
NORMAL CONSISTENCY.

27.—*Significance.*—The use of a proper percentage of water in making the pastes* from which pats, tests of setting and briquettes are made, is exceedingly important, and affects vitally the results obtained.

28.—The determination consists in measuring the amount of water required to reduce the cement to a given state of plasticity, or to what is usually designated the normal consistency.

29.—Various methods have been proposed for making this determination, none of which has been found entirely satisfactory. The Committee recommends the following:

30.—*Method. Vicat Needle Apparatus.*—This consists of a frame (*K*), Fig. 2, bearing a movable rod (*L*), with the cap (*A*) at one end, and at the other end the cylinder (*B*), 1 cm. (0.39 in.) in diameter, the cap, rod and cylinder weighing 300 gr. (10.58 oz.). The rod, which can be held in any desired position by a screw (*F*), carries an indicator, which moves over a scale (graduated to centimeters) attached to the frame (*K*). The paste is held by a conical, hard-rubber ring (*I*), 7 cm. (2.76 ins.) in diameter at the base, 4 cm. (1.57 ins.) high, resting on a glass plate (*J*), about 10 cm. (3.94 ins.) square.



Vicat Needle.
FIG. 2.

31.—In making the determination, the same quantity of cement as will be subsequently used for each batch in making the briquettes (but not less than

*The term "paste" is used in this report to designate a mixture of cement and water, and the word "mortar" a mixture of cement, sand and water.

less with such a paste.

35.—Having determined in this manner the proper percentage of water required to produce a neat paste of normal consistency, the proper percentage required for the sand mortars is obtained from an empirical formula.

36.—The Committee hopes to devise such a formula. The subject proves to be a very difficult one, and, although the Committee has given it much study, it is not yet prepared to make a definite recommendation.

TIME OF SETTING.

37.—*Significance.*—The object of this test is to determine the time which elapses from the moment water is added until the paste ceases to be fluid and plastic (called the "initial set"), and also the time required for it to acquire a certain degree of hardness (called the "final" or "hard set"). The former of these is the more important, since, with the commencement of setting, the process of crystallization or hardening is said to begin. As a disturbance of this process may produce a loss of strength, it is desirable to complete the operation of mixing and moulding or incorporating the mortar into the work before the cement begins to set.

38.—It is usual to measure arbitrarily the beginning and end of the setting by the penetration of weighted wires of given diameters.

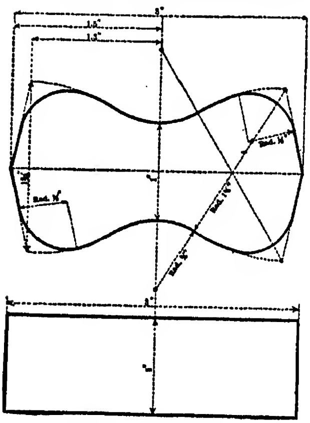
39.—*Method.*—For this purpose the Vicat Needle, which has already been described in Paragraph 30, should be used.

40.—In making the test, a paste of normal consistency is moulded and placed under the rod (L), Fig. 2, as described in Paragraph 31; this rod, bearing the cap (D) at one end and the needle (H), 1 mm. (0.039 in.) in diameter, at the other, weighing 300 gr. (10.58 oz.). The needle is then carefully brought in contact with the surface of the paste and quickly released.

41.—The setting is said to have commenced when the needle ceases to pass a point 5 mm. (0.20 in.) above the upper surface of the glass plate, and is

said to have terminated the moment the needle does not sink visibly into the mass.

42.—The test pieces should be stored in moist air during the test; this is accomplished by placing them on a rack over water contained in a pan and covered with a damp cloth, the cloth to be kept away from them by means of a wire screen; or they may be stored in a moist box or closet.



Details for Briquette.
FIG. 3.

43.—Care should be taken to keep the needle clean, as the collection of cement on the sides of the needle retards the penetration, while cement on the point reduces the area and tends to increase the penetration.

44.—The determination of the time of setting is only approximate, being materially affected by the temperature of the mixing water, the temperature and humidity of the air during the test, the percentage of water used, and the amount of moulding the paste receives.

STANDARD SAND.

45.—The Committee recognizes the grave objections to the standard quartz now generally used, especially on account of its high percentage of voids, the difficulty of compacting in the moulds, and its lack of uniformity; it has spent much time in investigating the various natural sands which appeared to be available and suitable for use.

46.—For the present, the Committee recommends the natural sand from Ottawa, Ill., screened to pass a sieve having 20 meshes per linear inch and retained on a sieve having 30 meshes per linear inch; the wires to have diameters of 0.0165 and 0.0112 in., respectively, *i. e.*, half the width of the opening in each case. Sand having passed the No. 20 sieve shall be considered standard when not more than one per cent. passes a No. 30 sieve, after one minute continuous sifting of a 500-gram sample.

47.—The Sandusky Portland Cement Company, of Sandusky, Ohio, has agreed to undertake the preparation of this sand, and to furnish it at a price only sufficient to cover the actual cost of preparation.

FORM OF BRIQUETTE.

48.—While the form of the briquette recommended by a former Committee of the Society is not wholly satisfactory, this Committee is not prepared to suggest any change, other than rounding off the corners by curves of ½-in. radius, Fig. 3.

MOULDS.

49.—The moulds should be made of brass, bronze or some equally non-

52.—All proportions should be stated by weight; the quantity of water to be used should be stated as a percentage of the dry material.

53.—The metric system is recommended because of the convenient relation of the gram and the cubic centimeter.

54.—The temperature of the room and the mixing water should be as near 21° Cent. (70° Fahr.) as it is practicable to maintain it.

55.—The sand and cement should be thoroughly mixed dry. The mixing should be done on some non-absorbing surface, preferably plate glass. If the mixing must be done on an absorbing surface it should be thoroughly dampened prior to use.

56.—The quantity of material to be mixed at one time depends on the number of test pieces to be made; about 1,000 gr. (35.28 oz.) makes a convenient quantity to mix, especially by hand methods.

57.—The Committee, after investigation of the various mechanical mixing machines, has decided not to recommend any machine that has thus far been devised, for the following reasons:

(1) The tendency of most cement is to "ball up" in the machine, thereby preventing the working of it into a homogeneous paste; (2) there are no means of ascertaining when the mixing is complete without stopping the machine, and (3) the difficulty of keeping the machine clean.

58.—*Method.*—The material is weighed and placed on the mixing table, and a crater formed in the centre, into which the proper percentage of clean water is poured; the material on the outer edge is turned into the crater by the aid of a trowel. As soon as the water has been absorbed, which should not require more than one minute, the operation is completed by vigorously kneading with the hands for an additional 1½ minutes, the process being similar to that used in kneading dough. A sand-glass affords a convenient guide for the time of kneading. During the operation of mixing the hands should be protected by gloves, preferably of rubber.

MOULDING.

59.—Having worked the paste or mortar to the proper consistency, it is at once placed in the moulds by hand.

60.—The Committee has been unable to secure satisfactory results with the

present moulding machines; the operation of machine moulding is very slow, and the present types permit of moulding but one briquette at a time, and are not practicable with the pastes or mortars herein recommended.

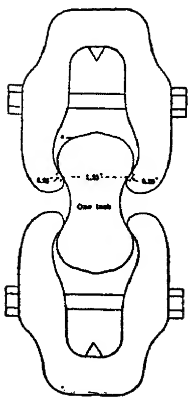
61.—*Method.*—The moulds should be filled at once, the material pressed in firmly with the fingers and smoothed off with a trowel without ramming; the material should be heaped up on the upper surface of the mould, and, in smoothing off, the trowel should be drawn over the mould in such a manner as to exert a moderate pressure on the excess material. The mould should be turned over and the operation repeated.

62.—A check upon the uniformity of the mixing and moulding is afforded by weighing the briquettes just prior to immersion, or upon removal from the moist closet. Briquettes which vary in weight more than 3 per cent. from the average should not be tested.

STORAGE OF THE TEST PIECES.

63.—During the first 24 hours after moulding the test pieces should be kept in moist air to prevent them from drying out.

64.—A moist closet or chamber is so easily devised that the use of the damp cloth should be abandoned if possible. Covering the test pieces with a damp cloth is objectionable, as commonly used, because the cloth may dry out unequally, and, in consequence, all the test pieces are not maintained under the same condition. Where a moist closet is not available, a cloth may be used and kept uniformly wet by immersing the ends in water. It should be kept from direct contact with the test pieces by means of a wire screen or some similar arrangement.



Form of Clip.
FIG. 5.

65.—A moist closet consists of a soapstone or slate box, or a metal-lined wooden box—the metal lining being covered with felt and this felt kept wet. The bottom of the box is so constructed as to hold water, and the sides are provided with cleats for holding glass shelves on which to place the briquettes. Care should be taken to keep the air in the closet uniformly moist.

66.—After 24 hours in moist air the test pieces for longer periods of time should be immersed in water maintained as near 21° Cent. (70° Fahr.) as practicable; they may be stored in tanks or pans, which should be of non-corrodible material.

TENSILE STRENGTH.

67.—The tests may be made on any standard machine. A solid metal clip, as shown in Fig. 5, is recommended. This clip is to be used without cushioning at the points of contact with the test specimen. The bearing at each point of contact should be ¼ in. wide, and the distance between the centre of contact on the same clip should be 1¼ ins.

constant volume.

70.—*Methods.*—Tests for constancy of volume are divided into two classes: (1) normal tests, or those made in either air or water maintained at about 21° Cent. (70° Fahr.), and (2) accelerated tests, or those made in air, steam or water at a temperature of 45° Cent. (115° Fahr.) and upward. The test pieces should be allowed to remain 24 hours in moist air before immersion in water or steam or preservation in air.

71.—For these tests, pats, about 7½ cm. (2.95 ins.) in diameter, 1¼ cm. (0.49 in.) thick at the centre, and tapering to a thin edge, should be made, upon a clean glass plate [about 10 cm. (3.94 ins.) square], from cement paste of normal consistency.

72.—*Normal Test.*—A pat is immersed in water maintained as near 21° Cent. (70° Fahr.) as possible for 28 days, and observed at intervals; the pat should remain firm and hard and show no signs of cracking, distortion or disintegration. A similar pat is maintained in air at ordinary temperature, and observed at intervals.

73.—*Accelerated Test.*—A pat is exposed in any convenient way in an atmosphere of steam, above boiling water, in a loosely closed vessel, for three hours.

74.—To pass these tests satisfactorily the pats should remain firm and hard, and show no signs of cracking, distortion or disintegration.

75.—Should the pat leave the plate, distortion may be detected best with a straight-edge applied to the surface which was in contact with the plate.

76.—In the present state of our knowledge it cannot be said that cement should necessarily be condemned simply for failure to pass the accelerated

tests; nor can a cement be considered entirely satisfactory simply becaus has passed these tests.

Submitted on behalf of the Committee.

GEORGE S. WEBSTER,
Chairman
RICHARD L. HUMPHREY,
Secretary

Committee.
GEORGE S. WEBSTER,
RICHARD L. HUMPHREY,
GEORGE F. SWAIN,
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APPENDIX II.

CONSTITUTION OF PORTLAND CEMENT.

Clifford Richardson, in a paper read before the Association of Portland Cement Manufacturers, at Atlantic City, June 15, 1904, has advanced considerably the knowledge concerning the constitution of Portland cements.

Le Chatelier and, independently of him, Törnebohm have found, as a result of studies by microscopic methods, that clinker consists of four constituents—alit, belit, celit and felit, whose sections have distinct optical properties, and of a fifth amorphous isotropic mass which has no action upon polarized light. Alit and celit are the principal constituents of clinker.

Richardson, from his own work, concludes that clinker is a solid solution of silicates and aluminates; alit being a solution of tricalcic aluminate ($Al_2O_3 3.CaO$), in tricalcic silicate (SiO_2 $3CaO$), and celit a solution of dicalcic aluminate ($Al_2O_3.2CaO$) in dicalcic silicate ($SiO_2.2CaO$). The presence of iron, magnesia, etc., exerts no essential influence, although probably adding to the complexity of the solid solutions present.

The formation of clinker from pure chemicals at a temperature below fusion is probably due to diffusion and subsequent interaction; this has been shown for other solid substances, as, for example, in the production of barium sulphate and sodium carbonate from a finely pulverized mixture of sodium sulphate and barium carbonate maintained in continued close contact.

Concerning, therefore, the manufacture of cements Richardson states, from the viewpoint of the diffusion of solid substances, as shown by the above example, that finer grinding of the raw mixture would make possible the use of lower temperatures in burning, and that therefore the relative costs of fuel and fineness of grinding at any given locality will determine, from an economic standpoint, the fineness to which the raw materials should be ground.

Richardson's work, while not settling the constitution of cement mixtures, is of the greatest importance, not only for what it has already accomplished, but also for the possibilities and methods of investigation it suggests; and it may reasonably be expected that in a relatively short time the question of the constitution of cements will be made as clear as is that of the different forms of iron. His work corroborates the conclusion, previously stated in Chapter I., that a simple chemical analysis of the constituents present in a cement can, as yet, furnish little evidence of its quality or as to its fitness for use.

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